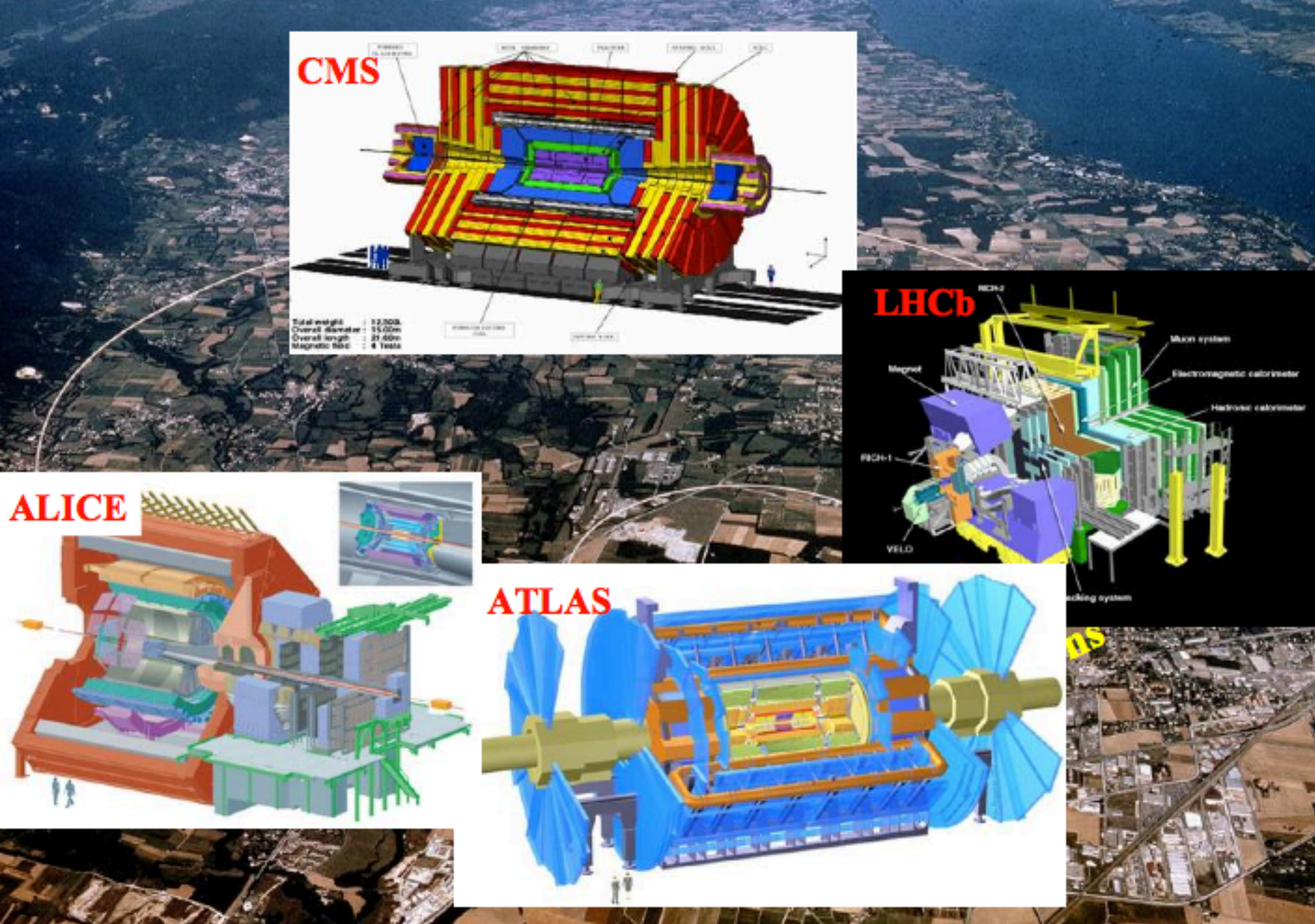
Particle Flow Calorimetry: A new generation of detectors

Felix Sefkow

Seminar, DESY, Zeuthen, June 23, 2010

The Large Hadron Collider (LHC)



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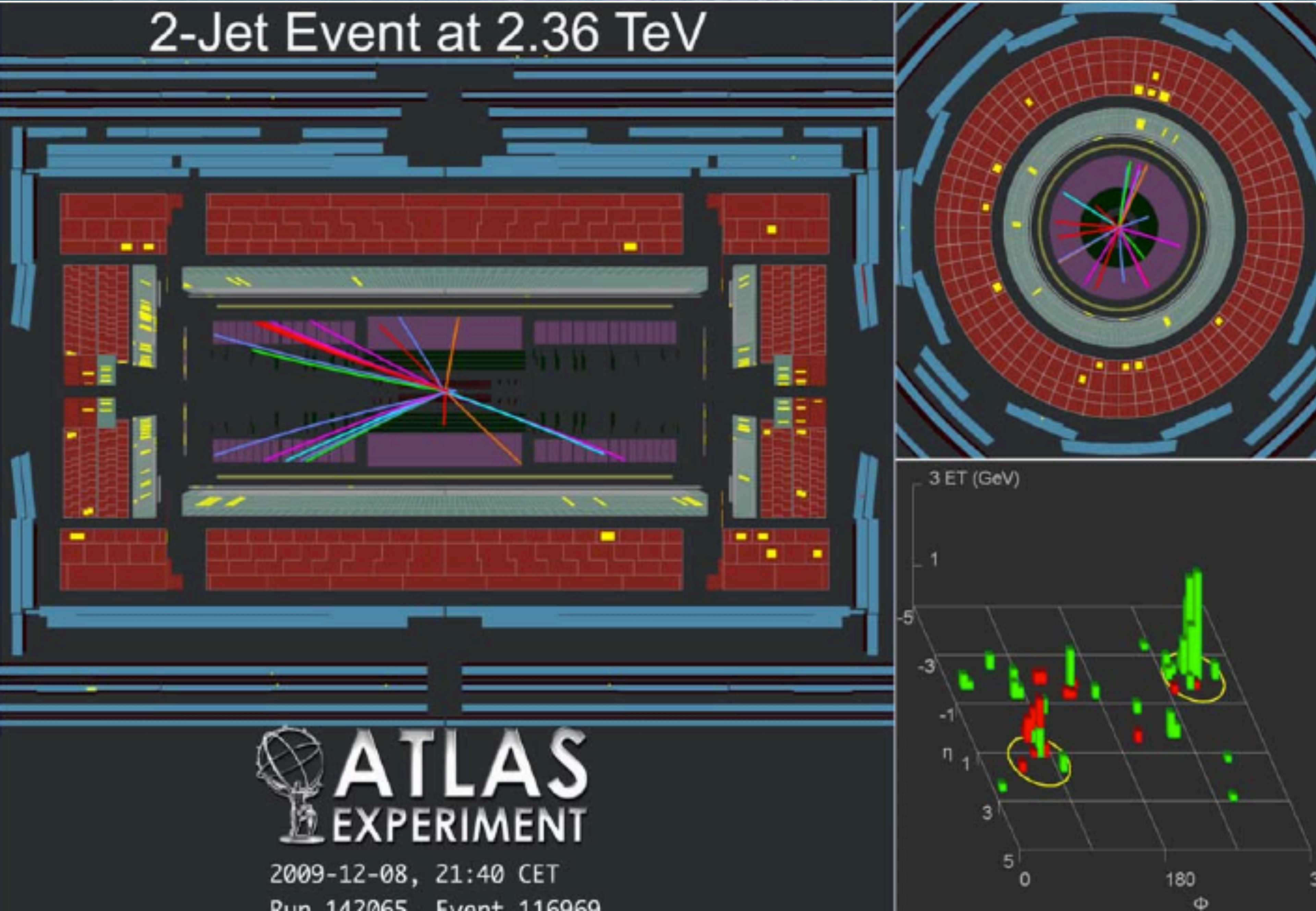
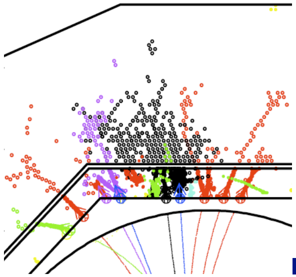




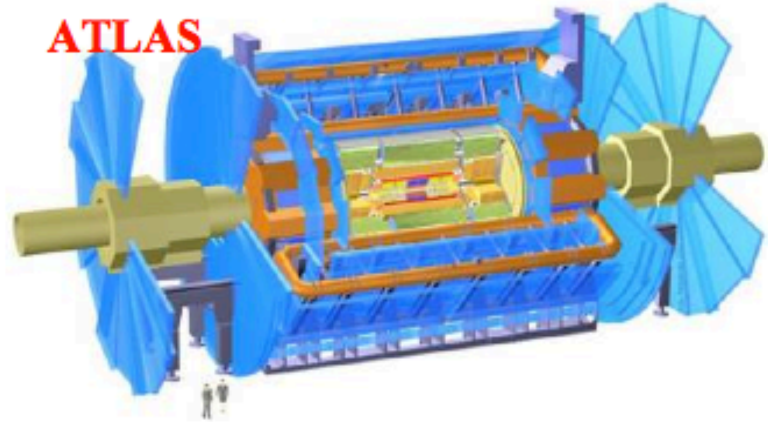
Future

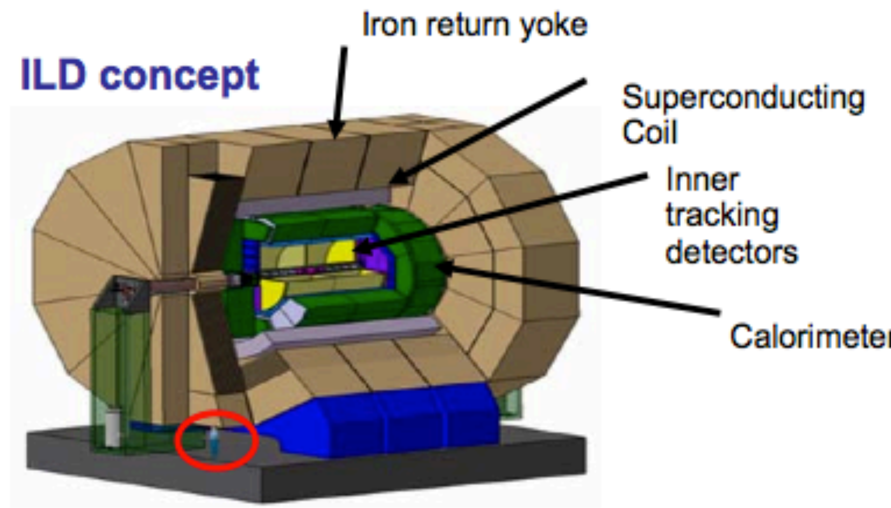
- Future directions in particle physics very much depends on LHC

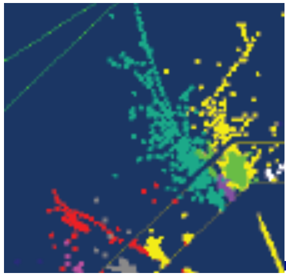
- Energy frontier:
  - LHC and upgrades (sLHC)
  - Linear Collider (ILC) or CLIC

- Other projects
  - Super b-factories
  - Neutrino physics

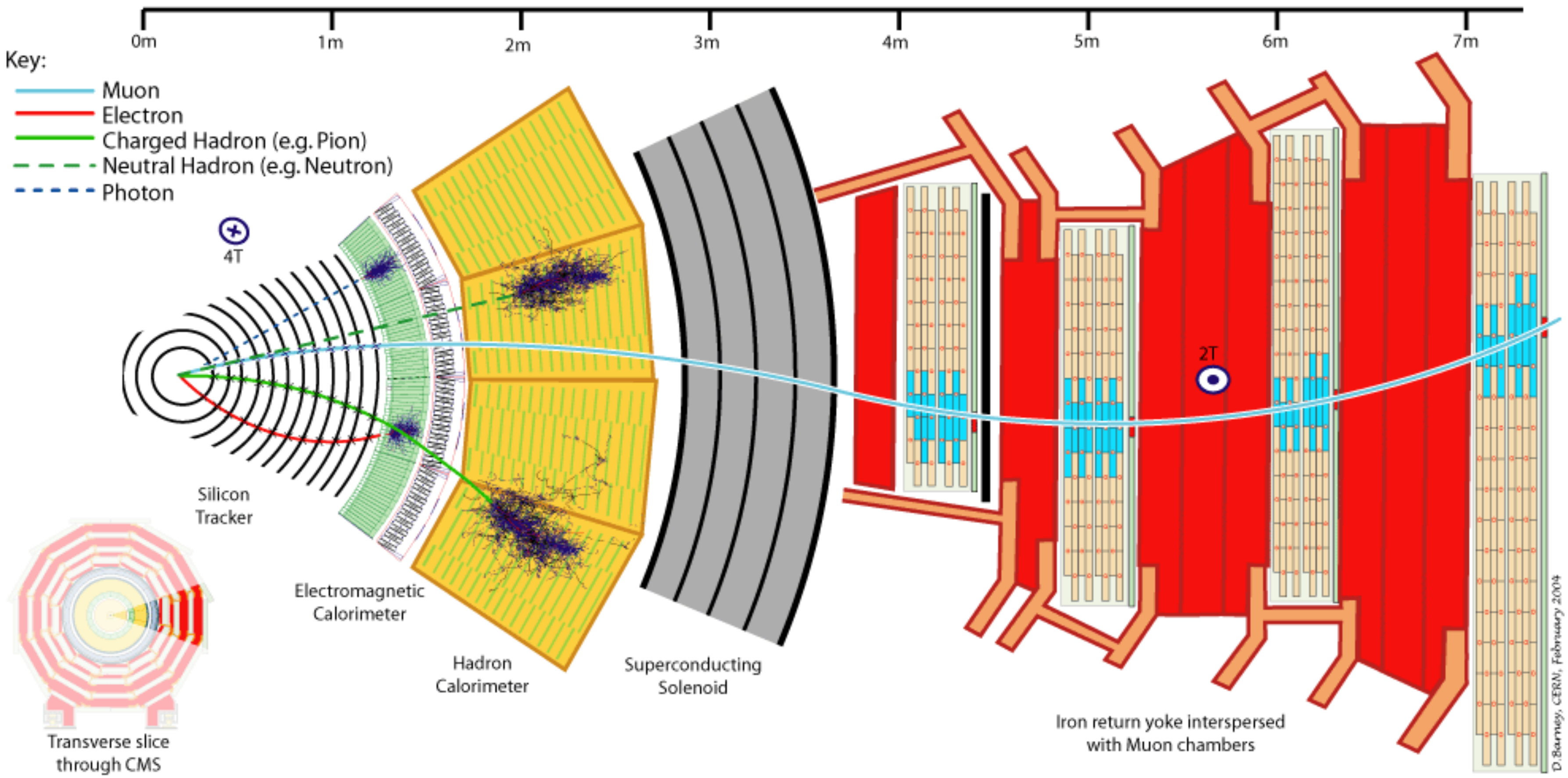
- Here: concentrate on energy frontier

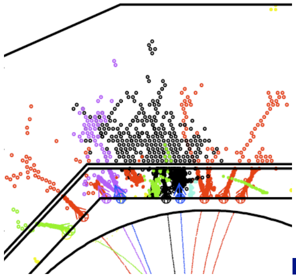




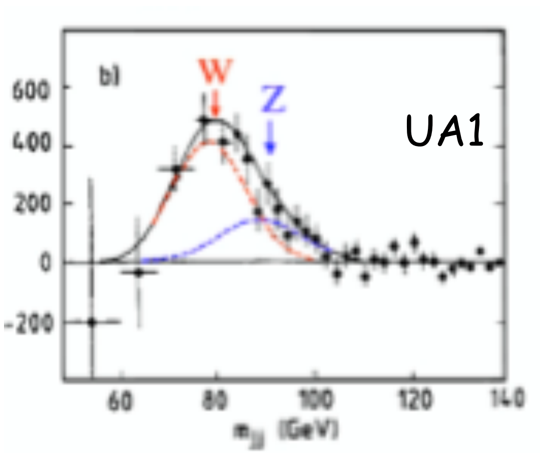


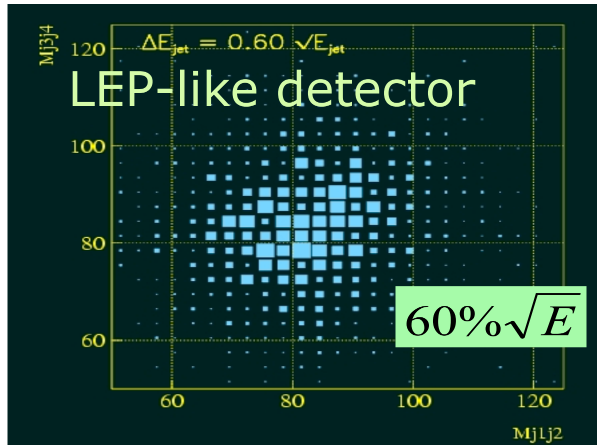
A generic collider detector

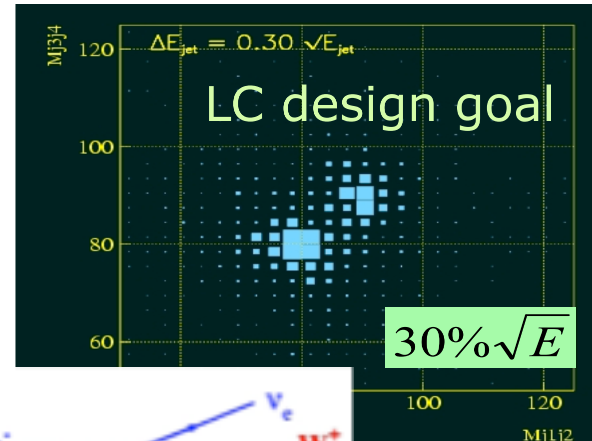


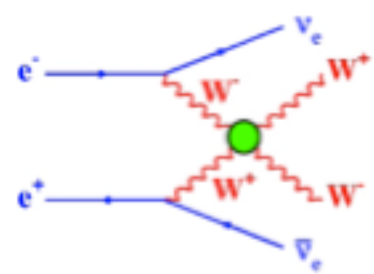


Challenge: W Z separation

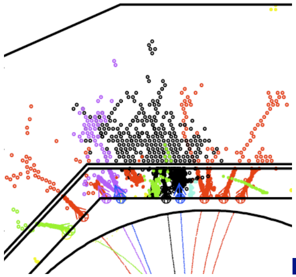








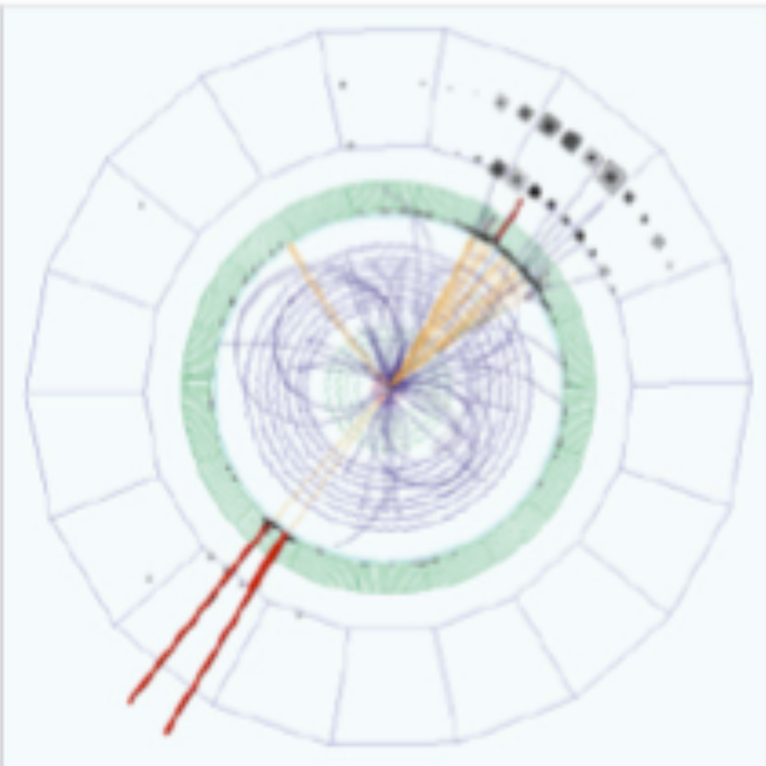
- At the Tera-scale, we need to do physics with W's and Z's as Belle and Babar do with D^+ and D_s
- Calorimeter performance for jets has to improve by a factor 2
- Rather young and dynamic development

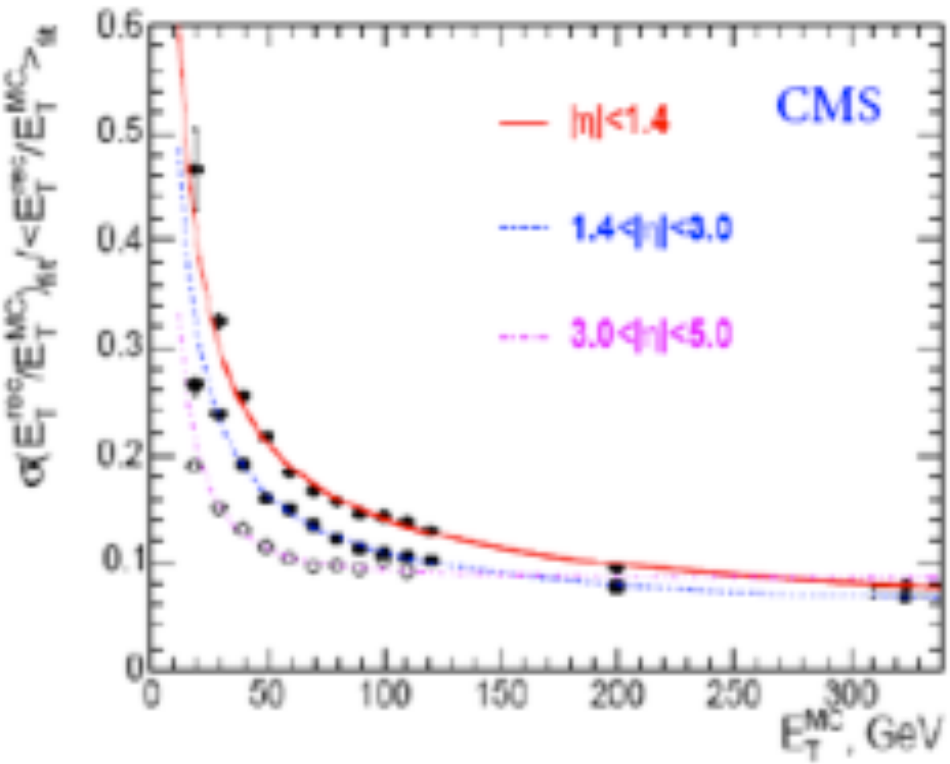


Outline

- Introduction:
  - intrinsic difficulties with hadron calorimetry
- The Particle Flow concept
- Making it a reality
  - Validate simulation
  - test the algorithms
  - develop and test the technologies

Jet energy resolution





> 100 % / √E

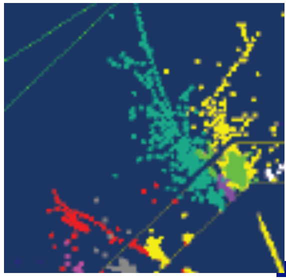
Electrons:

$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\ \mathrm{MeV}}{E} \oplus 0.44\ \%$$

0.6% at 50 GeV.

ECAL+HCAL energy resolution for pions:

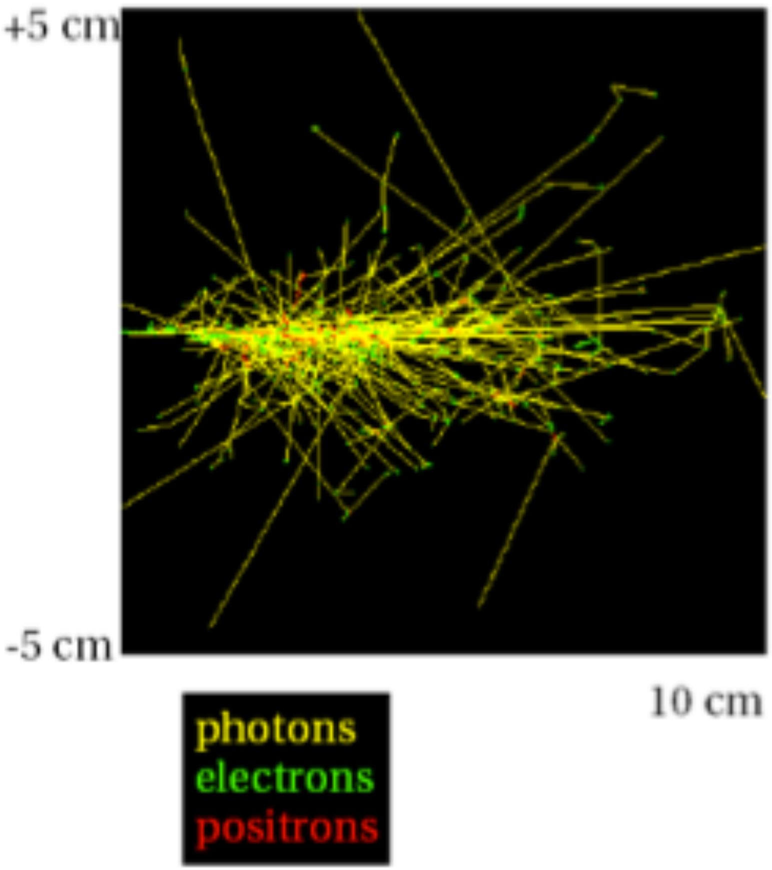
$$\frac{\sigma(E)}{E} = \frac{127\ \%}{\sqrt{E}} \oplus 6.5\ \%$$

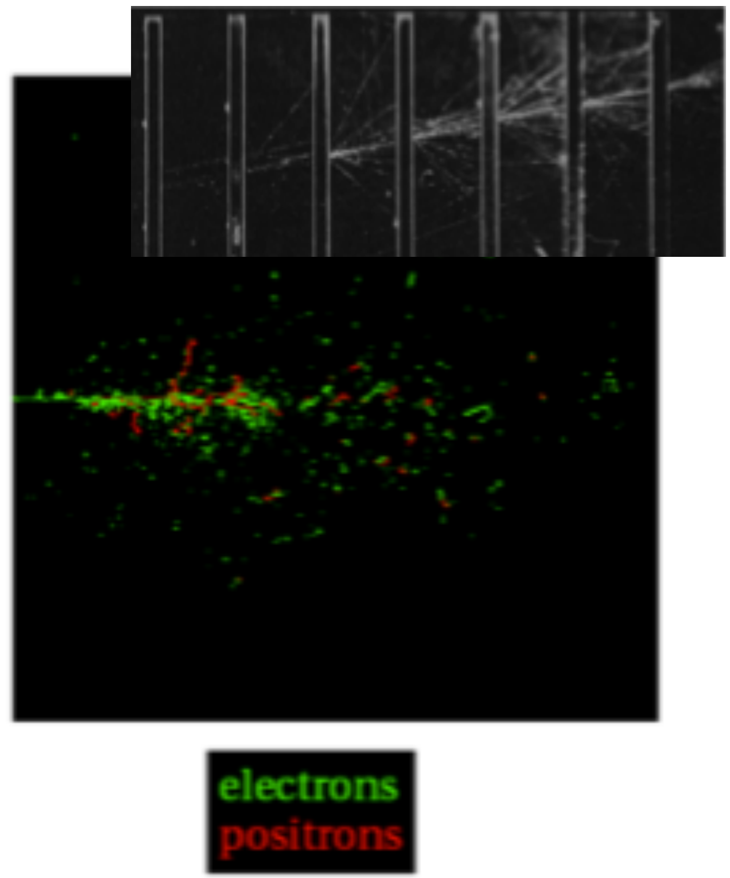


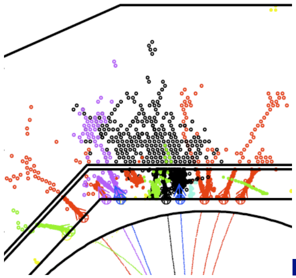
Electromagnetic showers

- Simulation: 1 GeV electron in lead

Lead absorbers in cloud chamber

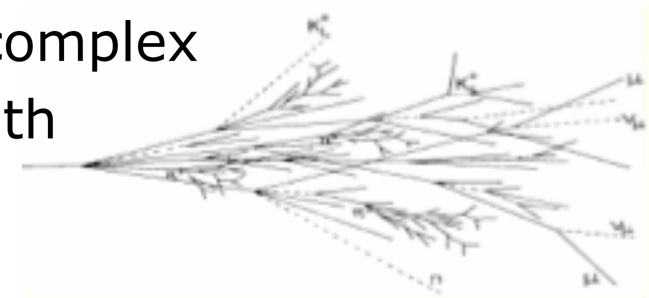


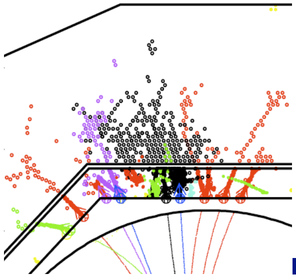




Hadron showers

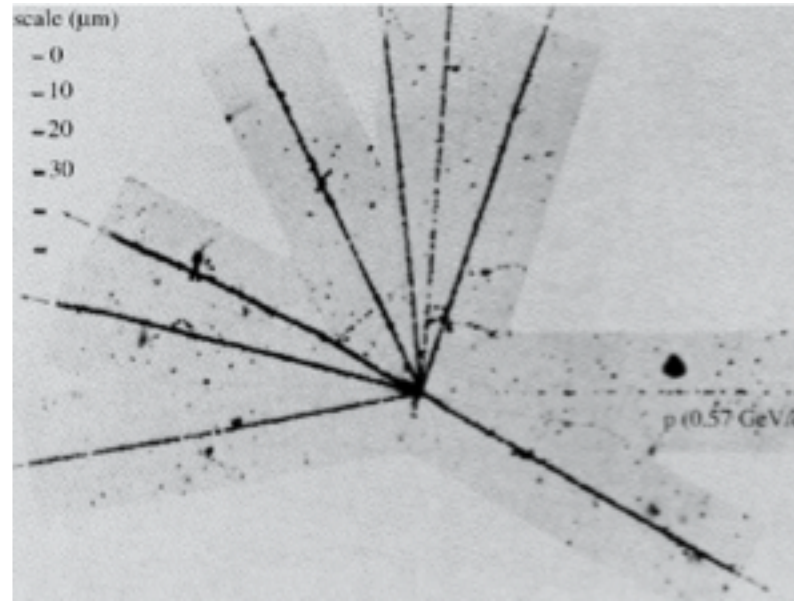
- Hadrons undergo strong interactions with detector (absorber) material
  - Charged hadrons: complementary to track measurement
  - Neutral hadrons: the only way to measure their energy
- In nuclear collisions numbers of secondary particles are produced
  - Partially undergo secondary, tertiary nuclear interactions ➔ formation of hadronic cascade
  - Electromagnetically decaying particles initiate em showers
  - Part of the energy is absorbed as nuclear binding energy or target recoil and invisible
- Similar to em showers, but much more complex
- Different scale: hadronic interaction length

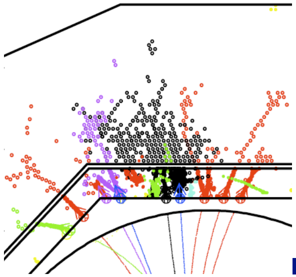




Hadronic interactions

- 1^{st} stage: the hard collision
  - Multiplicity scales with E
  - ~ 1/3 $\pi^0 \rightarrow \gamma\gamma$
  - Leading particle effect: depends on incident hadron type,
    - e.g fewer π^0 from protons
- 2^{nd} stage: spallation
  - Intra-nuclear cascade
    - Fast nucleons and other hadrons
  - Nuclear de-excitation
    - Evaporation of soft nucleons and α particles
    - Fission + evaporation

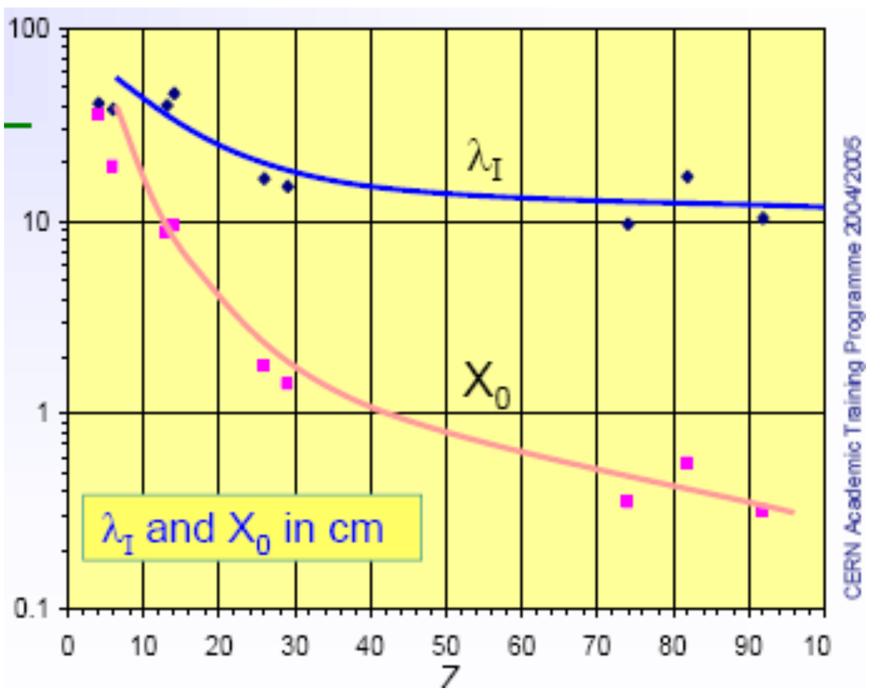


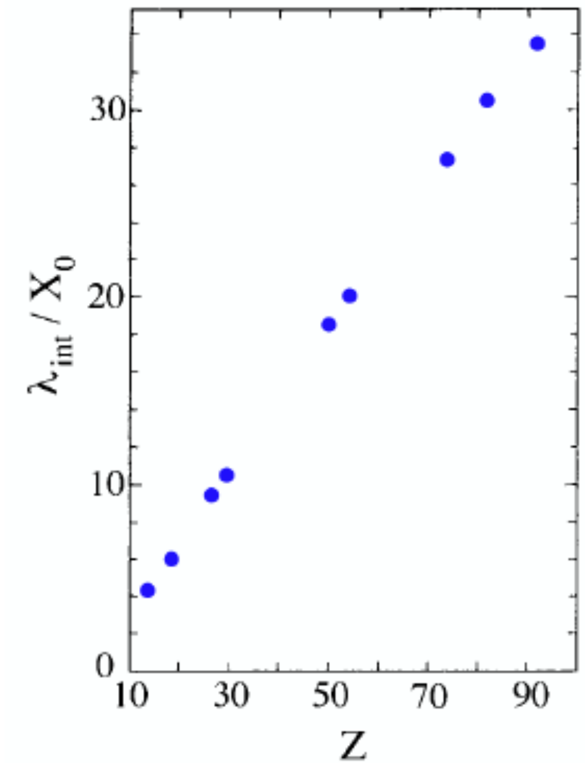


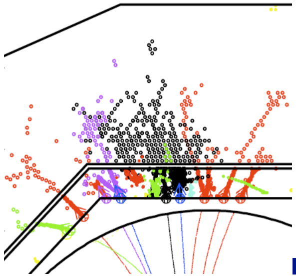
Hadronic interaction length

- λ_I: mean free path between nuclear collisions
- Hadron showers are much larger – how much, depends on Z
- Both scales present in every hadron shower

cm





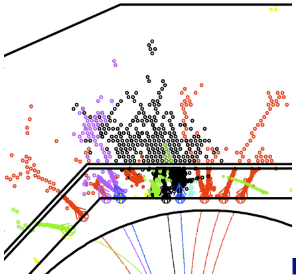


Electromagnetic fraction

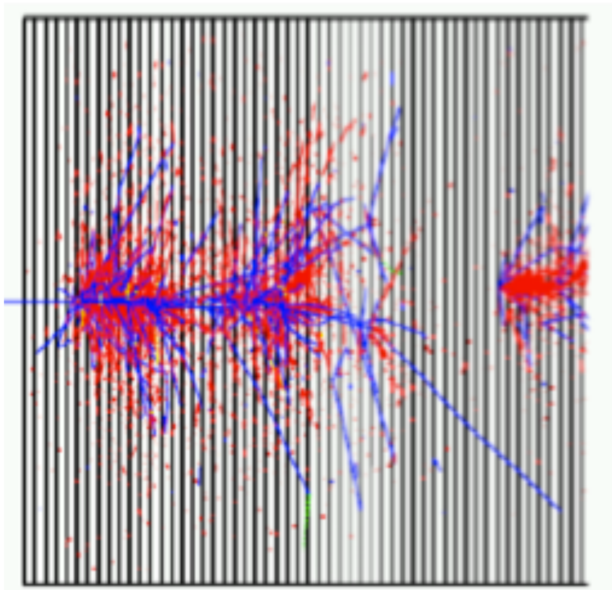
- In first collision, ~ 1/3 of produced particles are π^0
- $\pi^0 \rightarrow \gamma\gamma$ produce em shower, no further hadronic interaction
- Remaining hadrons undergo further interactions, more π^0

- π^0 production irreversible; "one way street"
  - Em fraction increases with energy
- Numerical example for copper
  - 10 GeV: f = 0.38; 9 charged h, 3 π^0
  - 100 GeV: f = 0.59; 58 charged h, 19 π^0
- Cf em shower: 100's e^+, 1000's e^-, millions γ

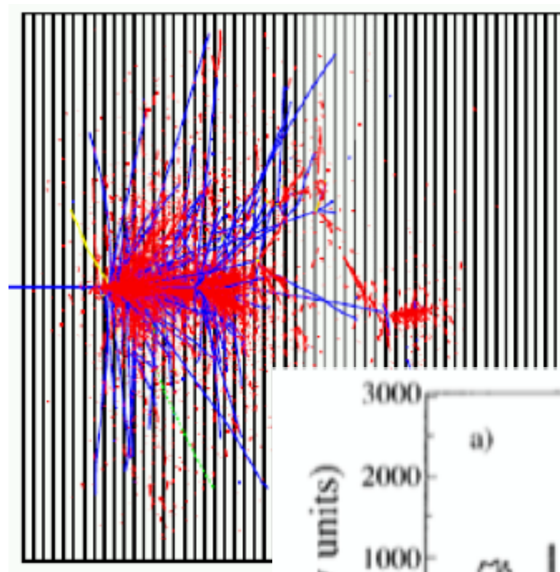
- Large fluctuations
  - E.g. charge exchange $\pi^+ p \rightarrow \pi^0 n$ (prb 1%) gives f_{em} = 100%



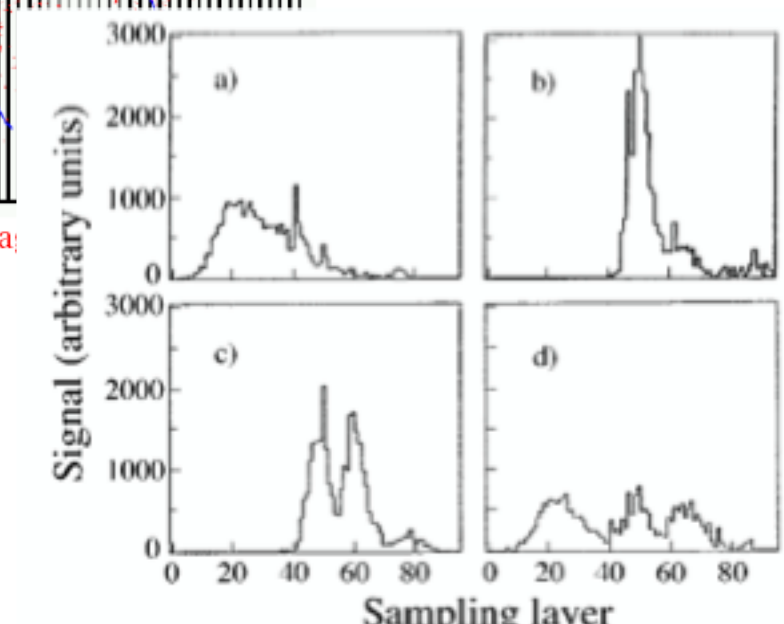
Fluctuations



blue = hadronic component

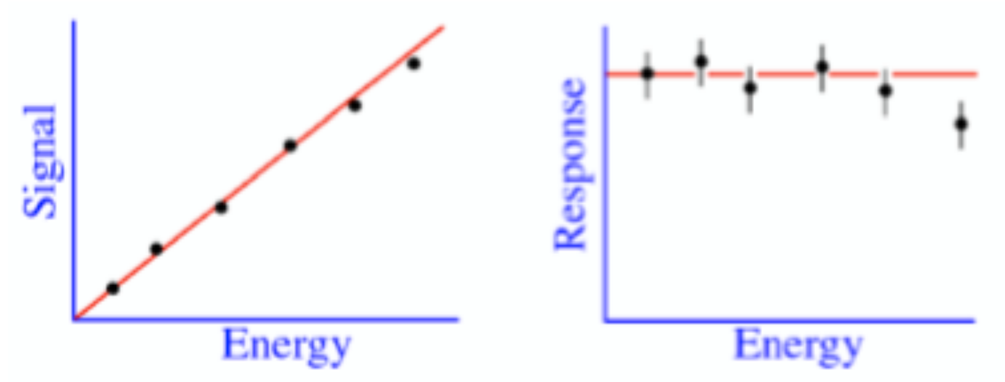


red = electroma

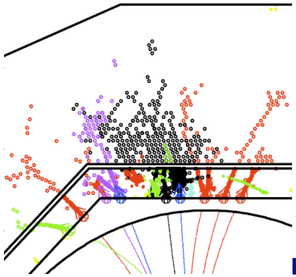


Leakage: in principle no problem
But: leakage fluctuations are!
(rule of thumb: $\sigma_{leak} \sim 4\ f_{leak}$)

Response and linearity



- A linear calorimeter has a constant response
- In general
  - Electromagnetic calorimeters are linear
  - Hadronic calorimeters are not:
    - Response depends on something which varies with energy
      - Em fraction, depth of interaction, leakage,
- No linearity – no superposition
  - 2 particles at 50 GeV not equal to 1 particle at 100 GeV
  - Non-linearity cannot simply be "calibrated away"



Em and hadronic response

- The response to the hadronic part of a hadron-induced shower is usually smaller than that to the electromagnetic part
  - Due to the invisible energy
  - Due to short range of spallation nucleons
  - Due to saturation effects for slow, highly ionizing particles
- e: em response, h: hadronic response
- e/π: ratio of response to electron vs pion induced shower

- $\boxed{e/\pi = e / [f_{em}\, e + (1 - f_{em})\, h] = e/h / [1 + f_{em}\,(e/h - 1)]}$

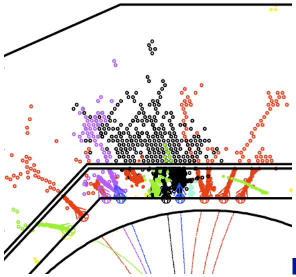
- Depends on E via f_{em} ➔ non-linearity
- Approaches 1 for e/h -> 1 or for f_{em} -> 1 (high energy limit)

Compensation

Different strategies, can be combined

- Hardware compensation
  - Reduce em response
    - High Z, soft photons
  - Increase had response
    - Ionization part
    - Neutron part (correlated with binding energy loss)
      - Tuneable via thickness of hydrogenous detector
  - Example ZEUS: uranium scintillator, 45 % / √E
- Software compensation
  - Identify em hot spots and down-weight
    - Requires high 3D segmentation
  - Example H1, Pb/Fe LAr, ~ 50% / √E

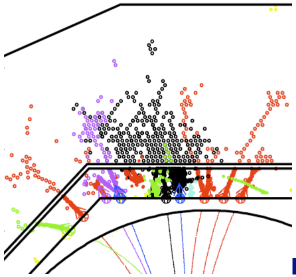
NB: Do not remove fluctuations in invisible energy



Hadron and jet calorimetry:

- Hadron showers: large variety of physics processes
  - With different detector responses
  - In general non-linear
  - Inevitably invisible energy; ultimate limit
  - Large fluctuations
  - Large volume, small signals
  - Difficult to model

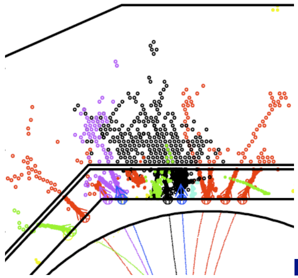
- Jet energy performance = hadron performance or worse



New concepts

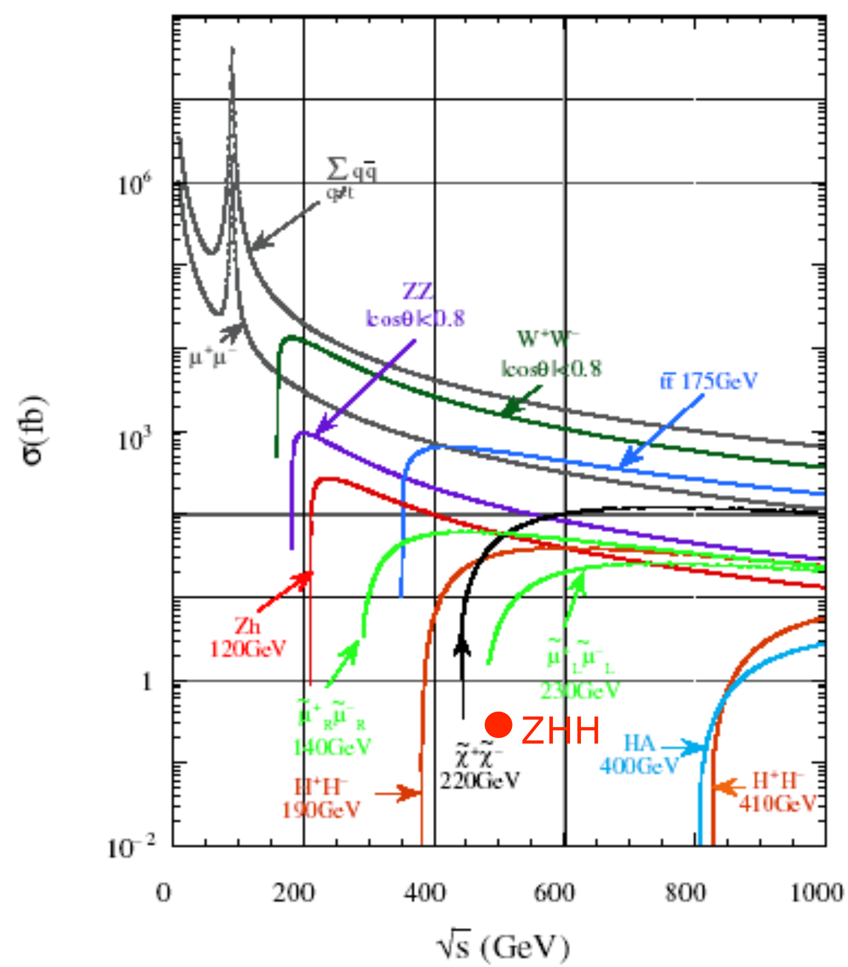
- Hardware (and software): ultimate compensation by directly <u>measuring</u> the electromagnetic component in each event, in addition to the total energy, and correcting for it
- ➔ dual readout calorimeters

- Software (and hardware): measure each particle in a jet individually and limit the problems of hadron calorimetry to the 10% or so of K_L and n in the jet; needs imaging granularity
- ➔ particle flow approach



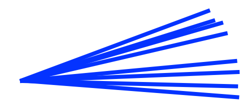
LC jet energies

- Q-Qbar events are boring; $E_{jet} = \sqrt{s}/2$ is wrong
- Mostly 4-, 6-fermion final states, ee➔ ttH ➔ 8 -10 jets
- At ILC 500: E_{jet} = 50…150 GeV
  - Mean pion energy 10 GeV
- At ILC 1 TeV: E_{jet} < ~ 300 GeV
- At CLIC (3 TeV) < ~ 500 GeV
- W reconstruction with
- $\sigma_m/m = 2.5/91$ need σ_E/E = 3.8%

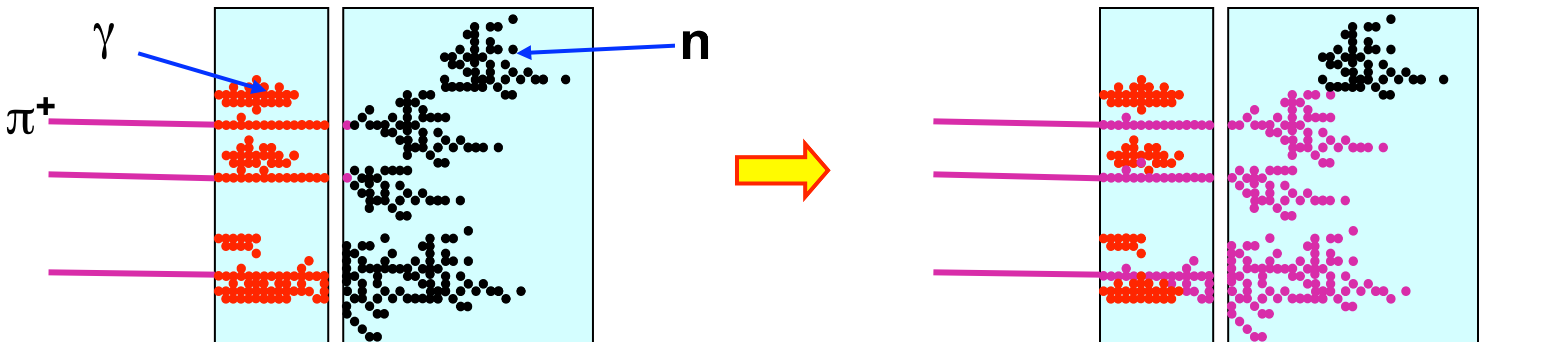


Particle Flow Calorimetry

- **In a typical jet :**
  - **60 % of jet energy in charged hadrons**
  - **30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)**
  - **10 % in neutral hadrons (mainly n and K_L)**



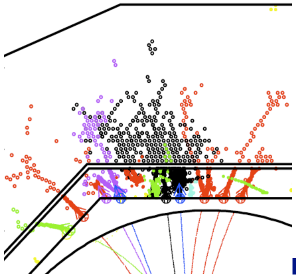
- **Traditional calorimetric approach:**
  - **Measure all components of jet energy in ECAL/HCAL !**
  - **~70 % of energy measured in HCAL:** $\sigma_\mathrm{E}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
  - **Intrinsically "poor" HCAL resolution limits jet energy resolution**



$E_{JET} = E_{ECAL} + E_{HCAL}$

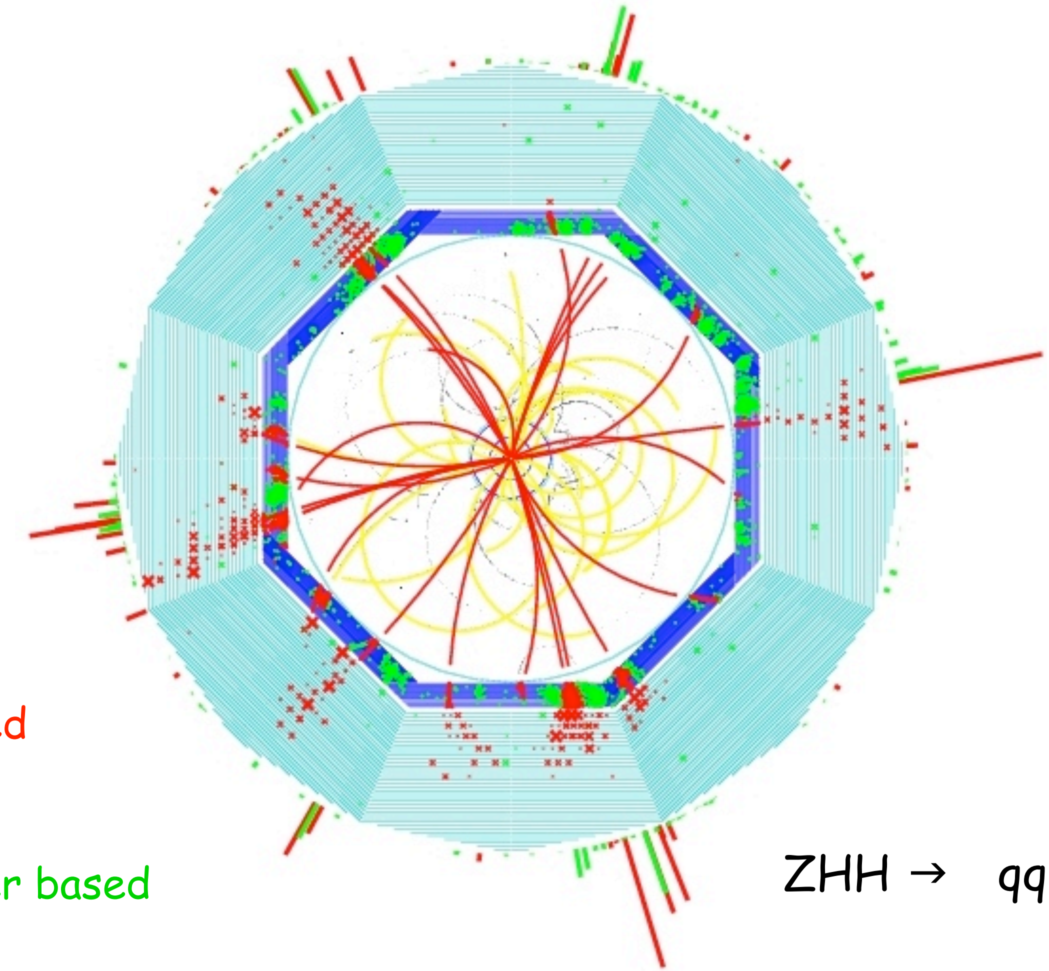
$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

- **Particle Flow Calorimetry paradigm:**
  - **charged particles measured in tracker (essentially perfectly)**
  - **Photons in ECAL:** $\sigma_\mathrm{E}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - **Neutral hadrons (ONLY) in HCAL**
  - **Only 10 % of jet energy from HCAL ⇒ much improved resolution**



Imaging calorimetry

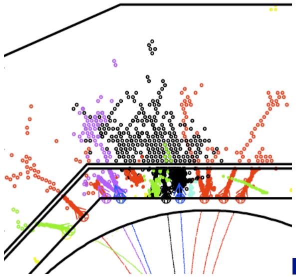
Reconstruct each particle individually



red:
track based

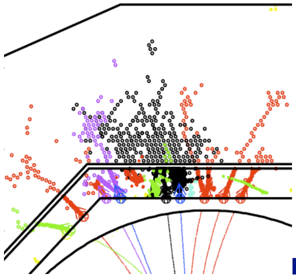
green:
calorimeter based

ZHH → qqbbbb



Calorimeter concept

- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- “no” material in front
  - stay inside coil
- small Moliere radius
  - to minimize shower overlap
- small granularity
  - to separate overlapping showers



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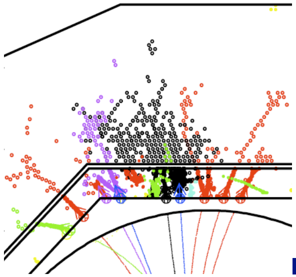
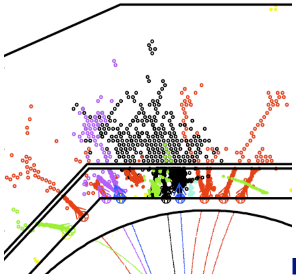


ILC detector concept

- PFLOW involves entire detector, not just calorimetery

- TPC for highest pattern recognition efficiency
- B=3.5T
- ECAL and HCAL inside (CMS-like) solenoid
- Highly segmented and compact calorimeters

- 2nd PFLOW-based concept: SiD, higher B, smaller R, Si tracker, same calorimeter technologies



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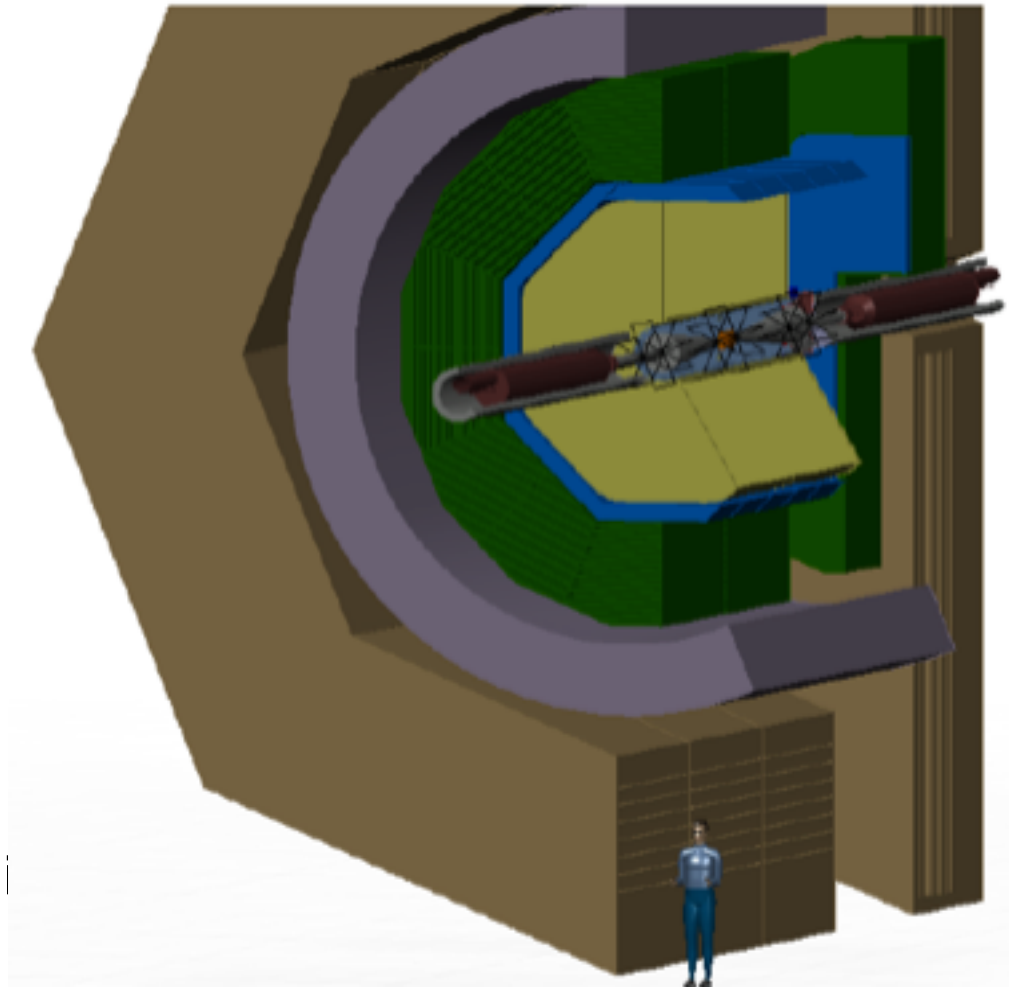
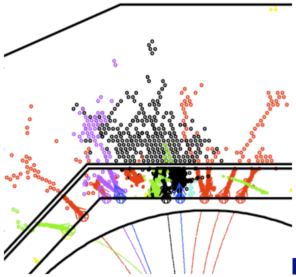
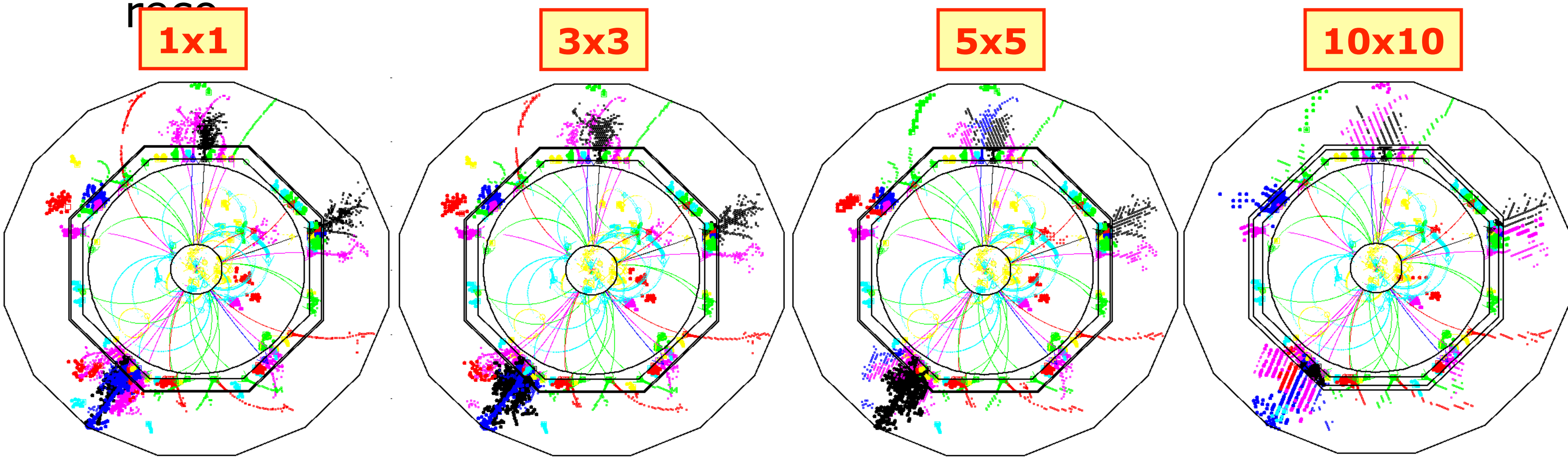


Calorimeter for ILC

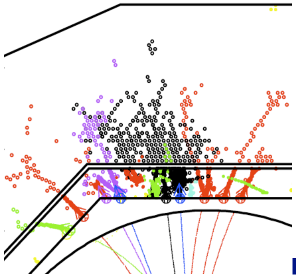


Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco



M.Thomson (Cambridge)



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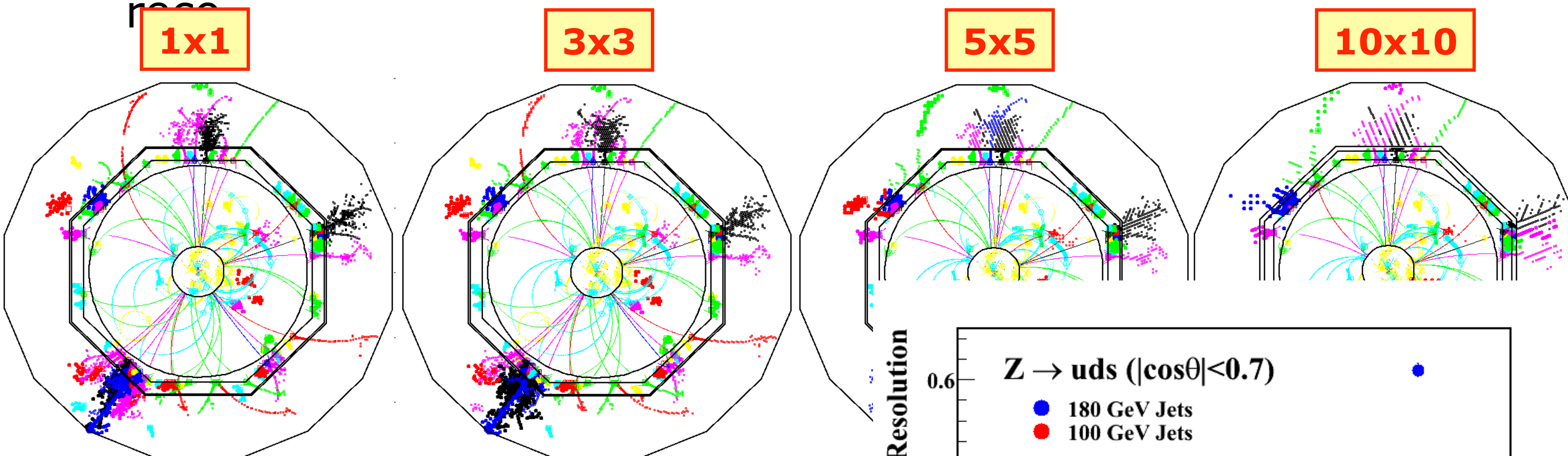

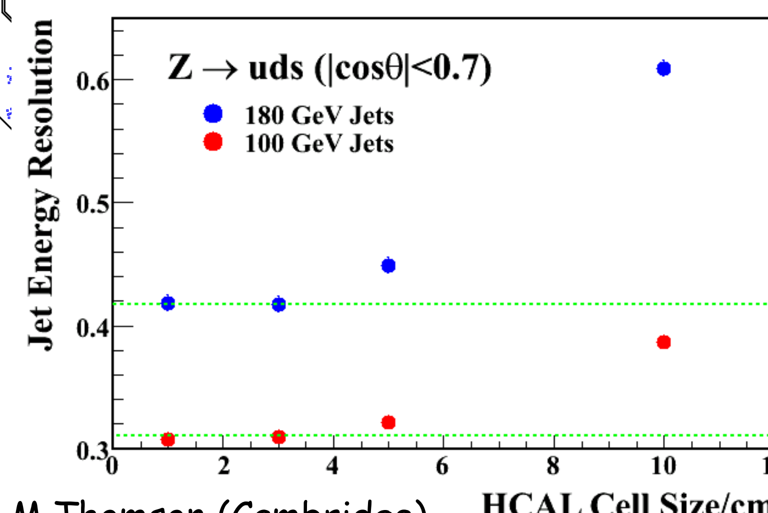

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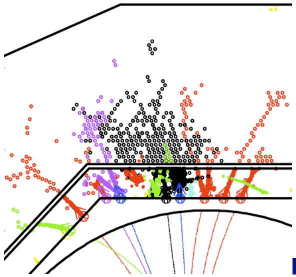

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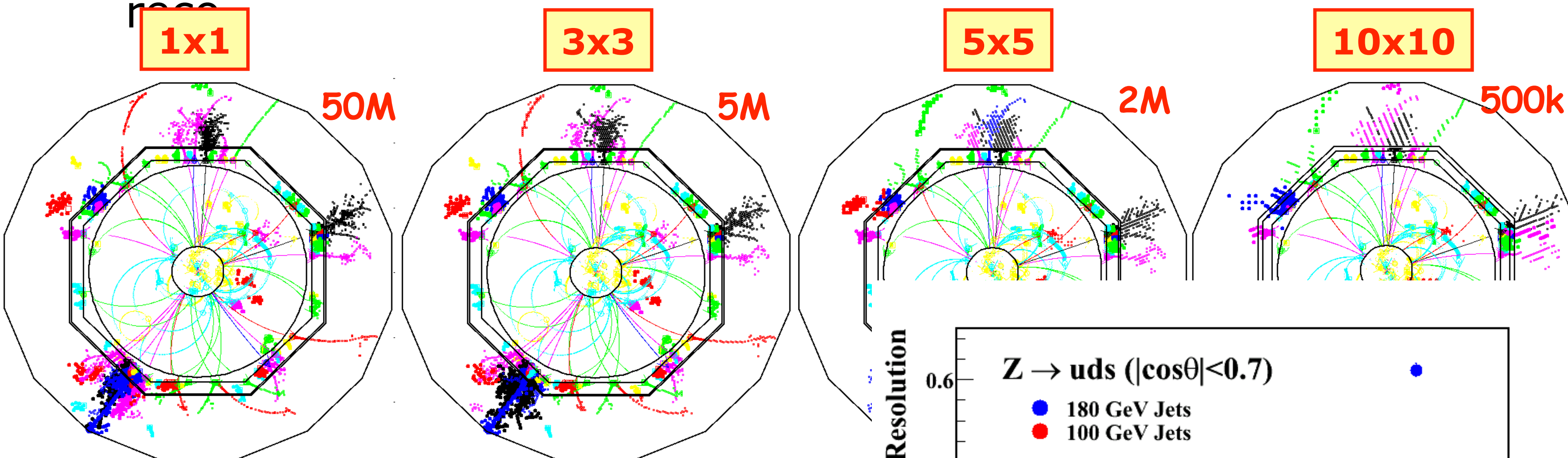
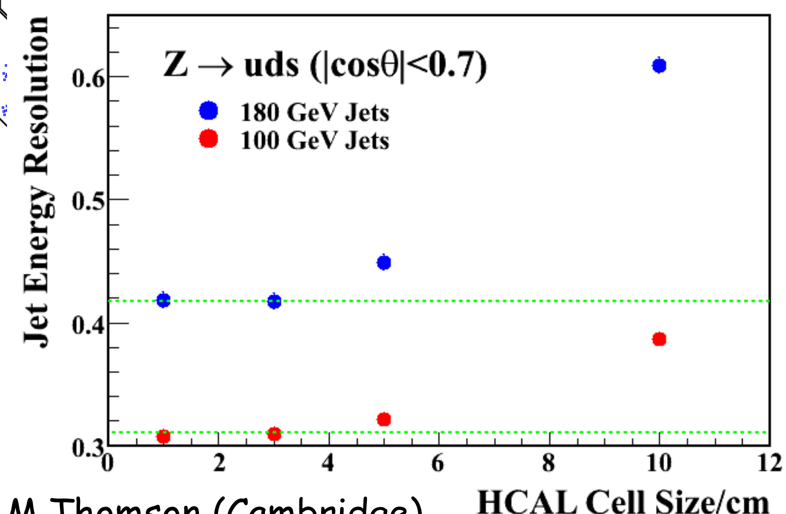
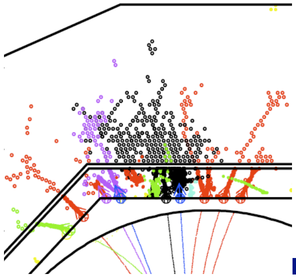


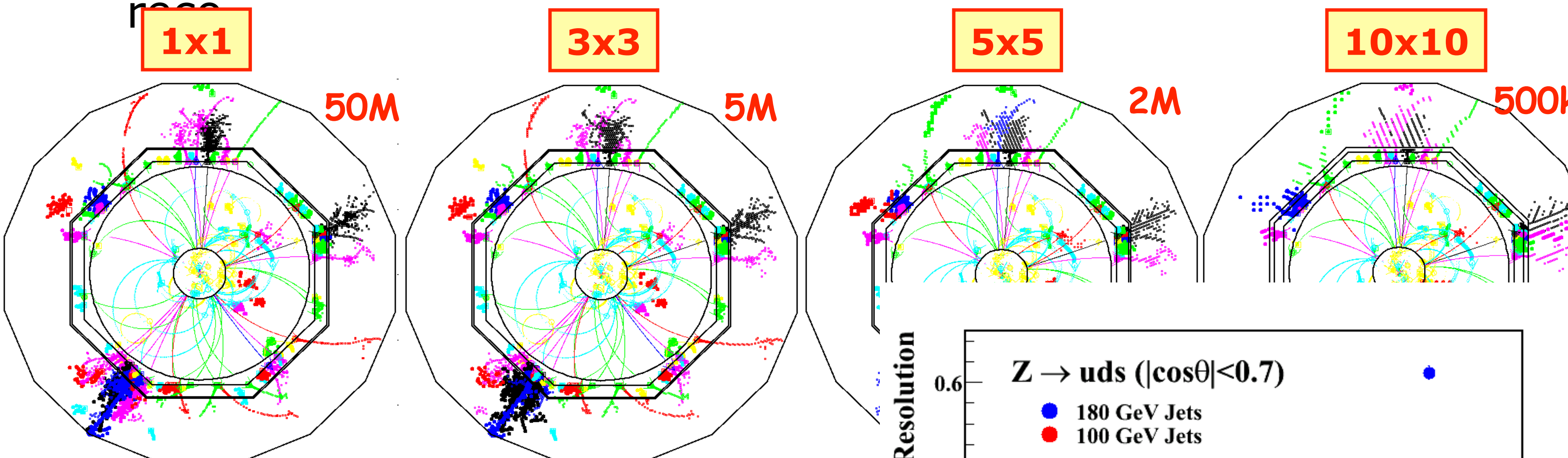


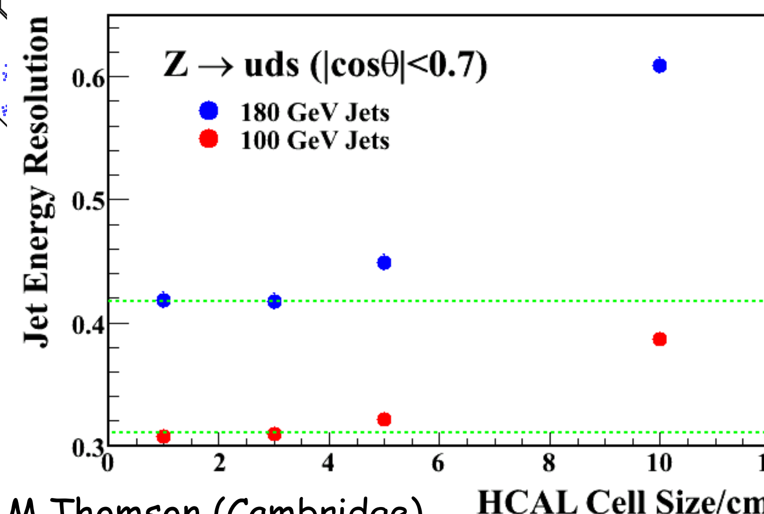
M.Thomson (Cambridge)



Tile granularity

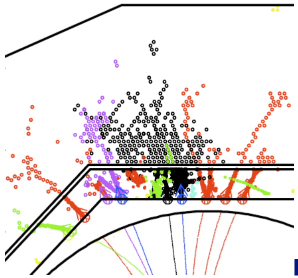
- Recent studies with PFLOW algorithm, full simulation and reco





M.Thomson (Cambridge)

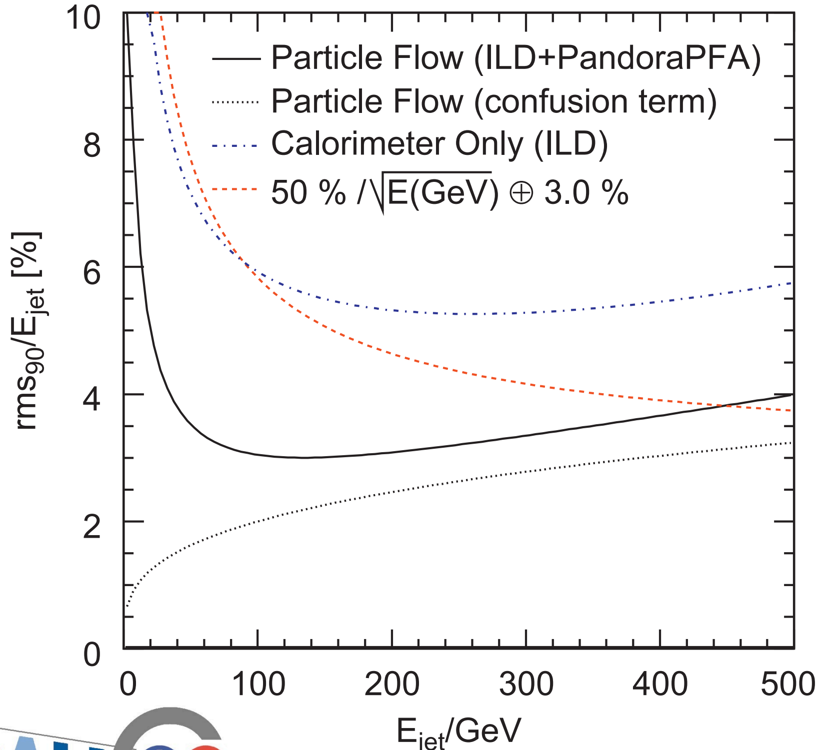
- Confirms earlier studies for test beam prototype
- 3x3 cm^2 nearly optimal

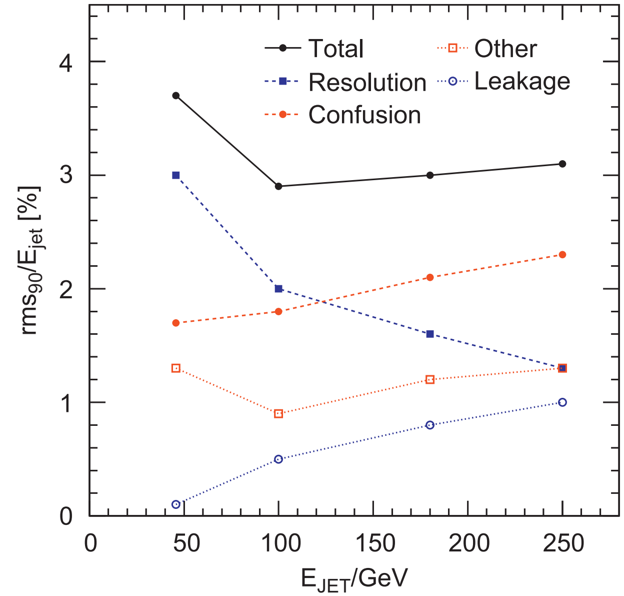


Understand particle flow performance

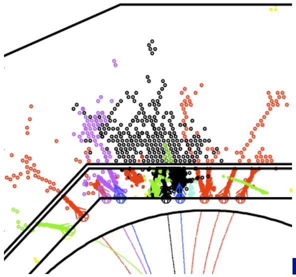
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3}\%$$

Resolution | Tracking | Leakage | Confusion





- Particle flow is always better
  - even at high jet energies
- HCAL resolution does matter
  - also for confusion term
- Leakage plays a role, too

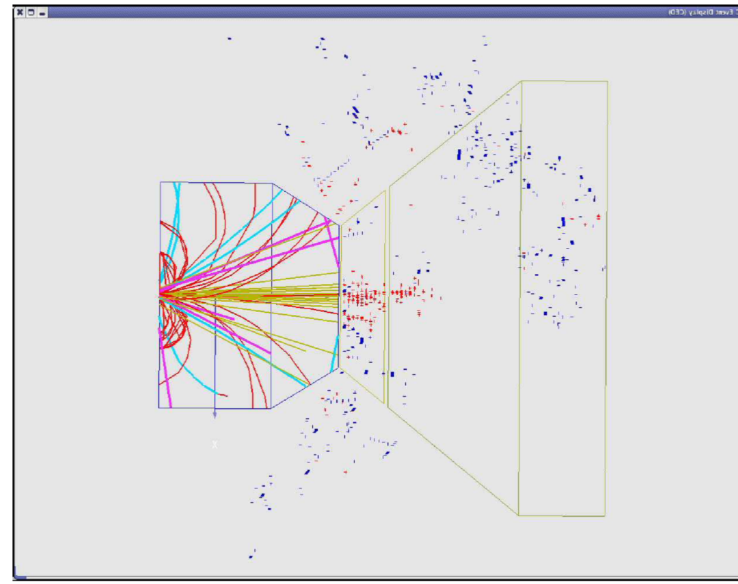


PFLOW detector concept

- Optimal use of all detector components: reconstruct each particle individually
- Interplay of highly granular detectors and sophisticated pattern recognition (clustering) algorithms
- Following detailed simulation and reconstruction studies, LC performance goals can be met
- Basic detector parameters thoroughly optimized
- A PFLOW detector is not cheap: do we believe in simulations?

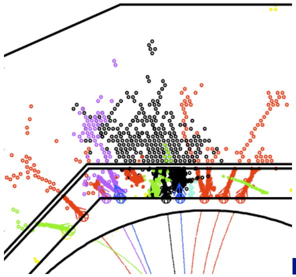
How to test it experimentally?

- "Jets" from thin targets?
  - Would require magnet spectroscopy and large acceptance ECAL + HCAL
    - Simulation study
  - Multi-million $ experiment
  - and still inconclusive
    - need to control target losses and acceptance losses at 1-2% level
    - model dependence

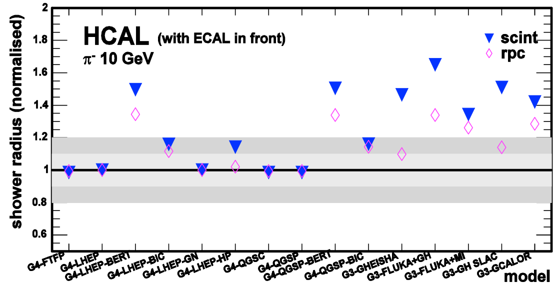


20 GeV pion, 0.8 T

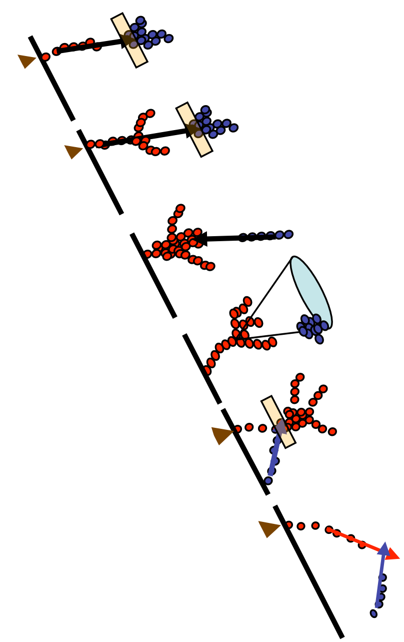
- Factorize the problem: check the ingredients
  - simulation
  - algorithms
  - technical performance

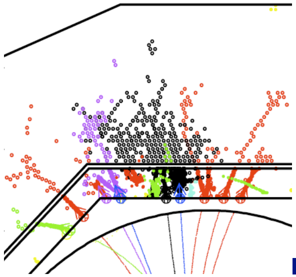


Critical questions



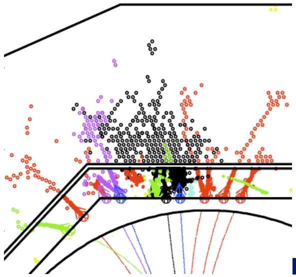
- Are the basic detector **performance** predictions confirmed?
- Are the **shower parameters** well enough simulated to predict PFLOW?
- Is the **substructure** actually there and well modele
- Can one realize the potential of **software compensation** for gain and linearity?
- Can we verify the "**double track resolution**" of a tracking calorimeter?
- Are **detector effects** under control?
- Can we **calibrate** millions of cells and control stability?
- Can we build the detector without spoiling it by **dead material** everywhere?
- What are the relative merits of **different technologies** for PFLOW?



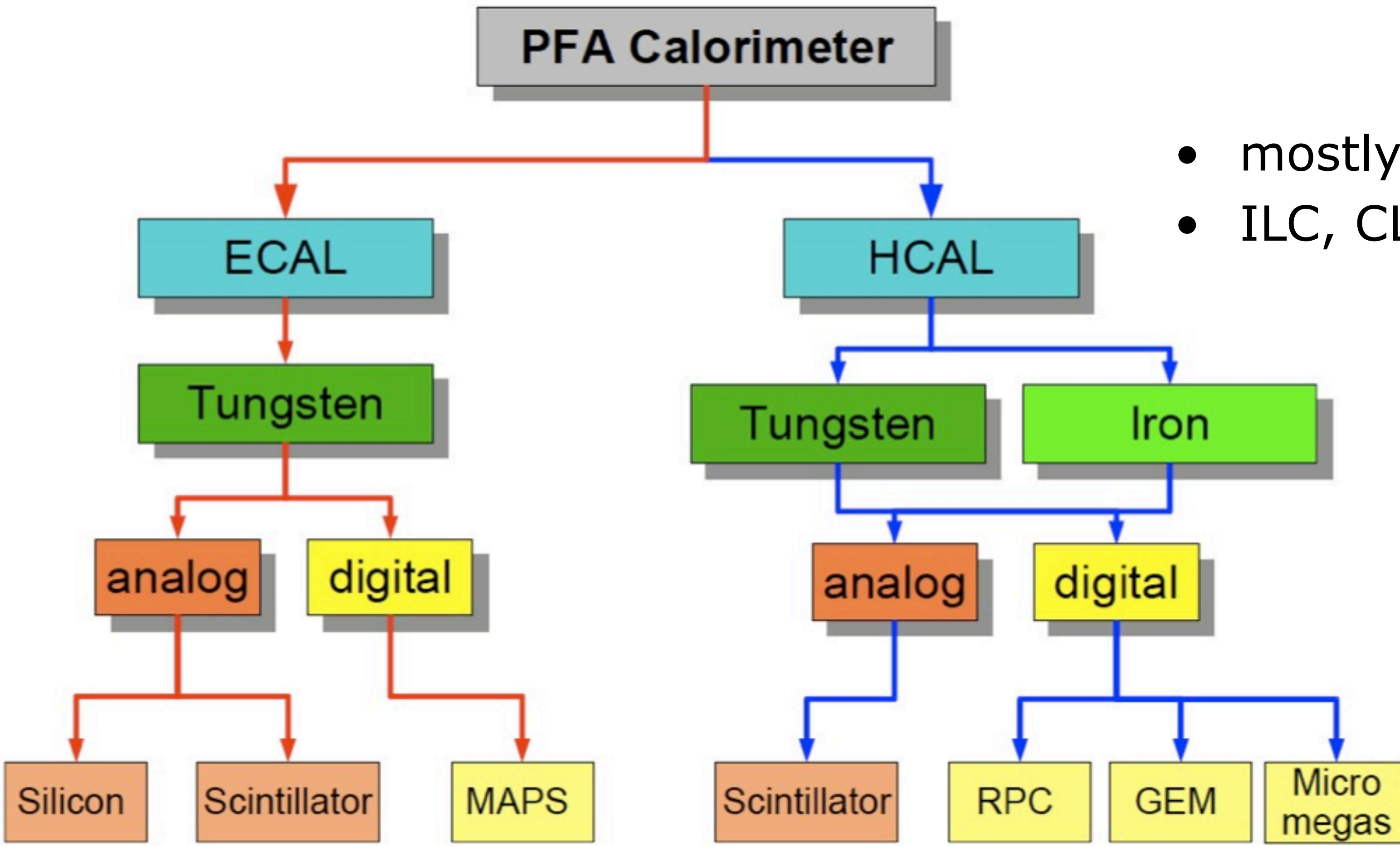


CALICE

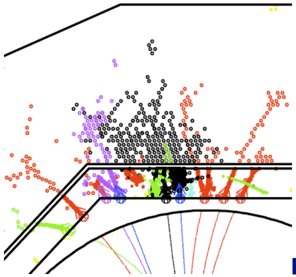
- We are more than 300 physicists and engineers from ~ 50 institutes in America, Europe and Asia
- Our goal: develop highly granular calorimeter options based on the particle flow approach for an e+e- linear collider
- Twofold approach:
  - Physics prototypes and test beam
    - Operational experience with new technologies, Test of shower simulation models, Development of reconstruction algorithms with real data
  - Technical prototypes
    - Realistic, scalable design (and costing) early next decade



Technology tree

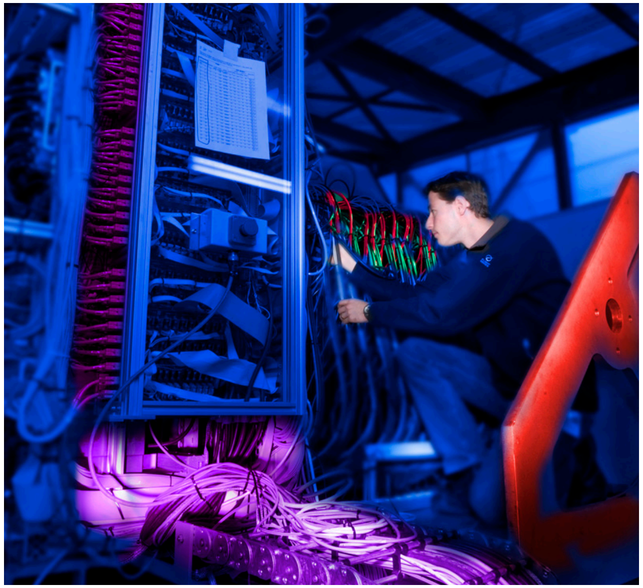


- mostly ILD, SiD
- ILC, CLIC



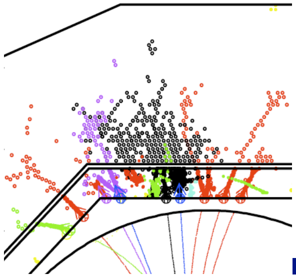
Overall status

- Major test beam campaigns at DESY, CERN and Fermilab
- 1st generation "physics" prototypes
- Mostly combined set-ups ECAL-HCAL

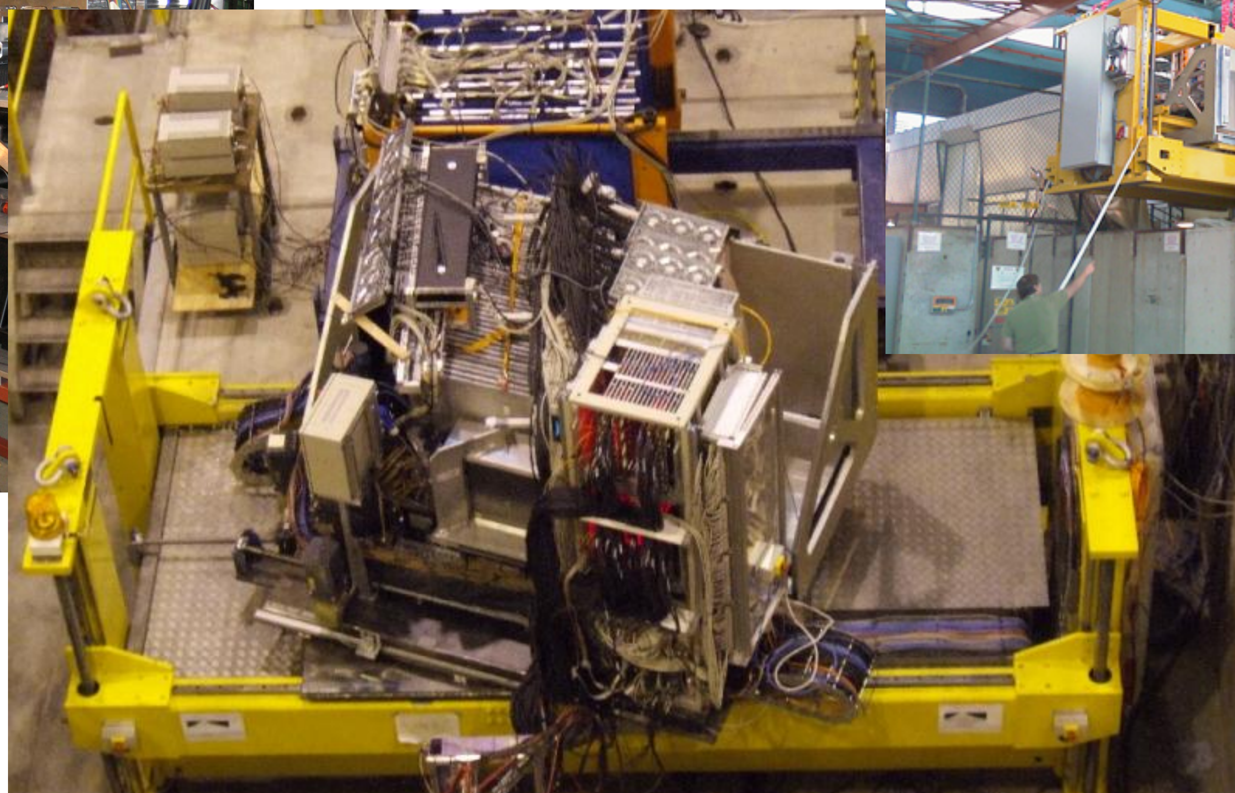


- Si W ECAL 2005-08
- Scint W ECAL 2007-09
- Scint Fe HCAL 2006-09
- RPC Fe HCAL to start end 2010

- 2nd generation "technical" prototypes: construction and commissioning ongoing, single or few layers
- Complete detectors to start with RPC-Fe HCAL 2011
- ECAL, Scint Fe HCAL later



Test beam experiments



CERN 2006-2007

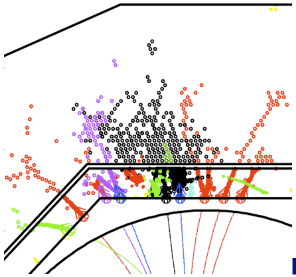
FNAL 2008..

DESY 2005

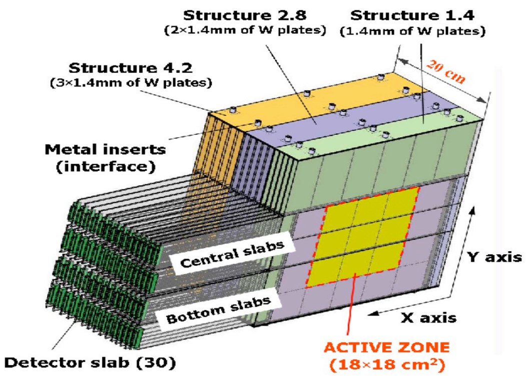
Validation of the simulations

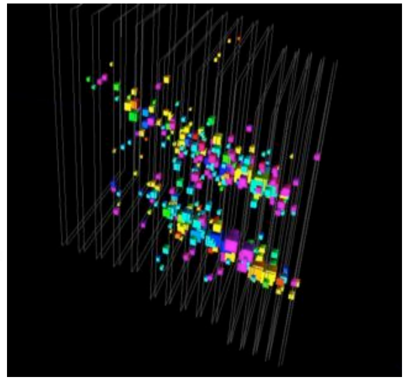
detector performance

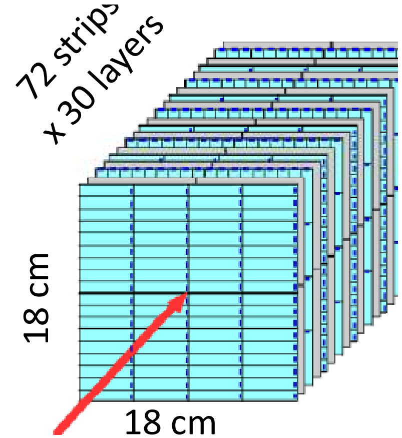
shower models

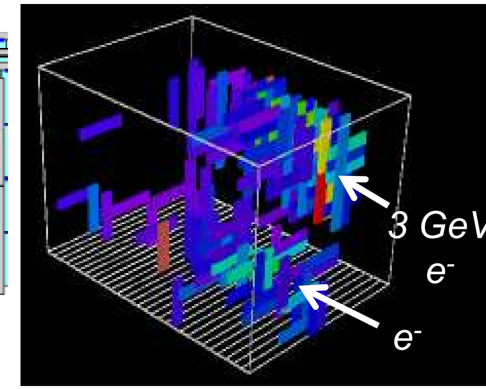


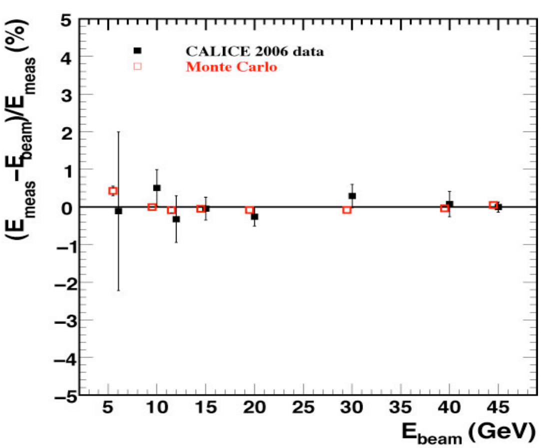
ECAL options

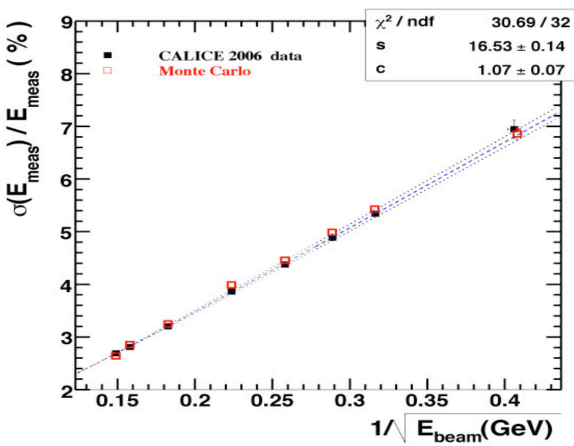


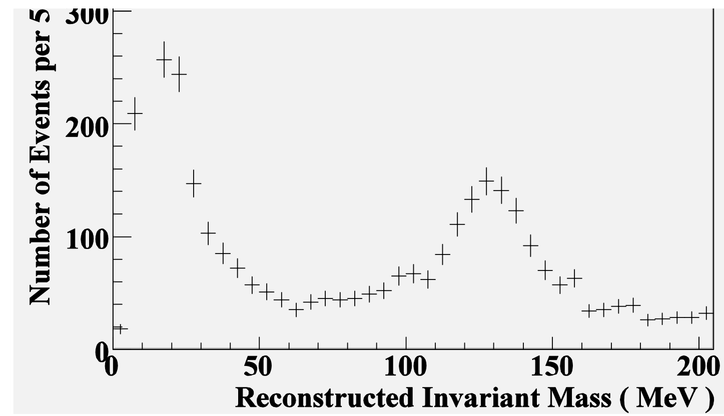




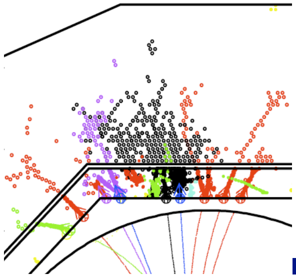






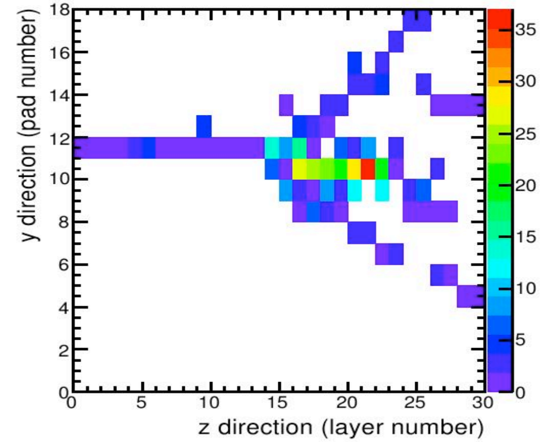


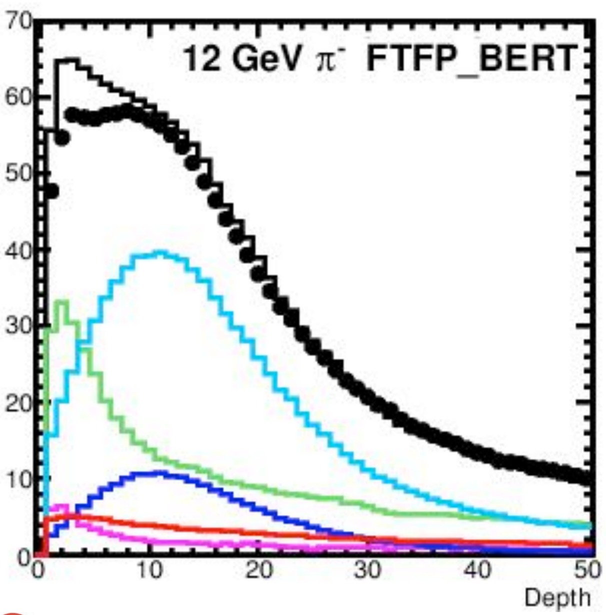
- W Si or Sci: common mechanics, similar electronics



Pions in the SiW ECAL

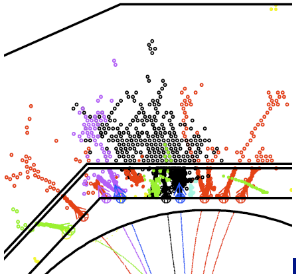
- test Geant 4 predictions with 1 cm^2 granularity
- sensitive to shower decomposition
- favor recent G4 physics lists
- certainly not perfect - certainly not bad either!



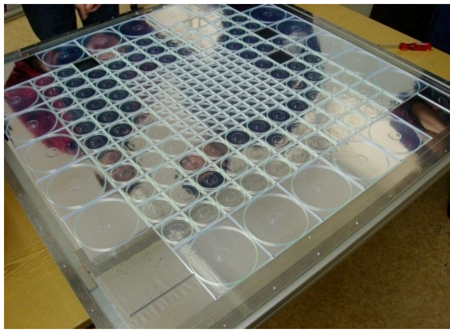


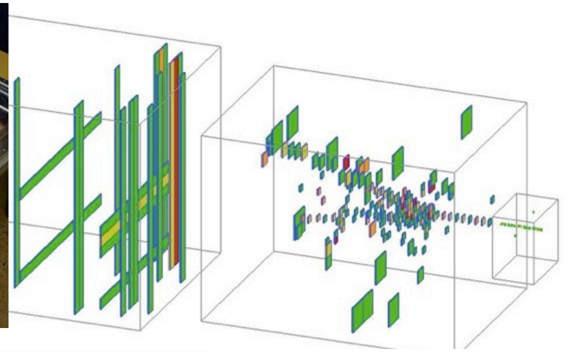
Shower Components:

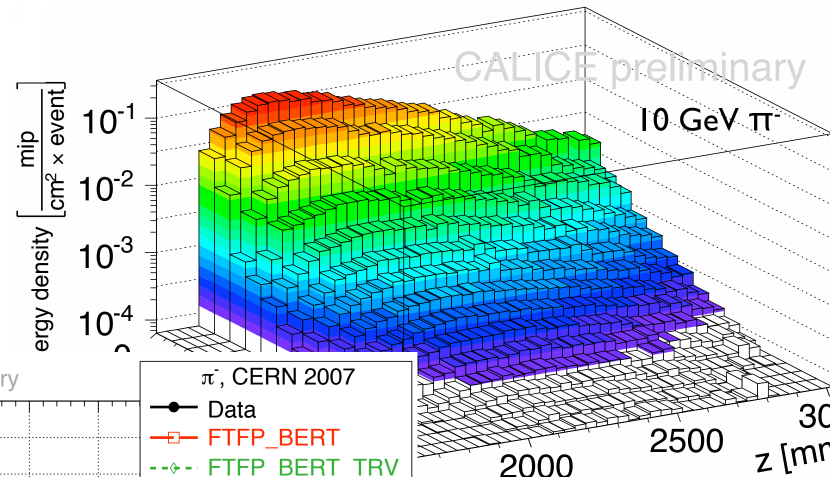
- electrons/positrons
  knock-on, ionisation, etc.
- protons
  from nuclear fragmentation
- mesons
- others
- sum

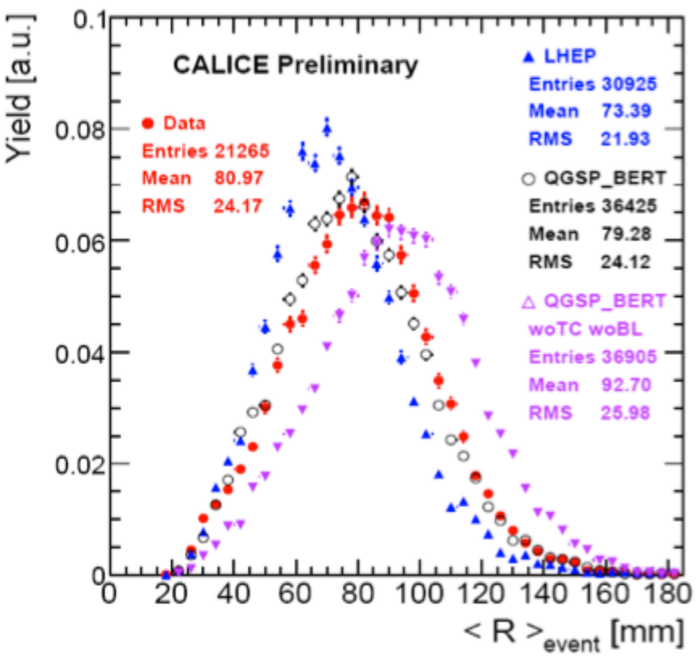


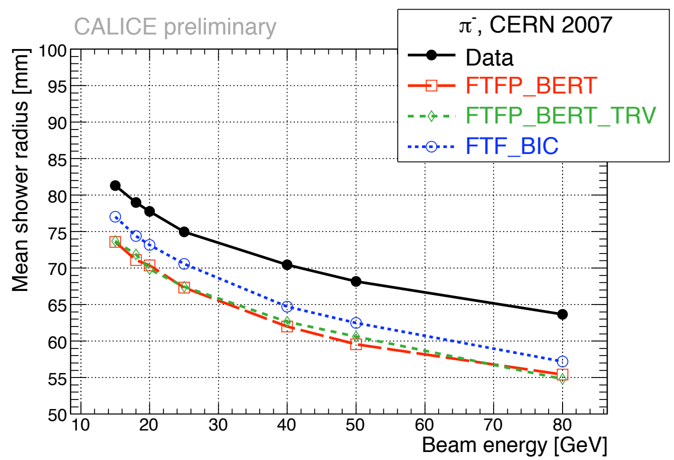
Fe Scint tile HCAL





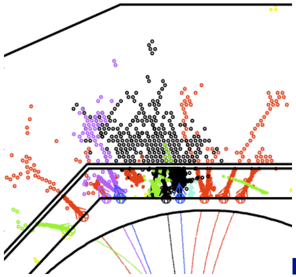




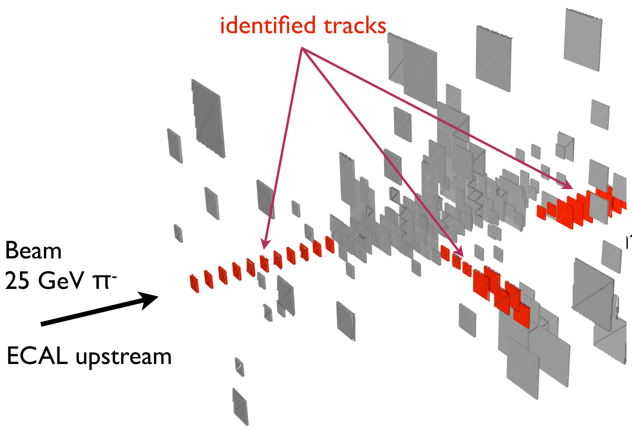


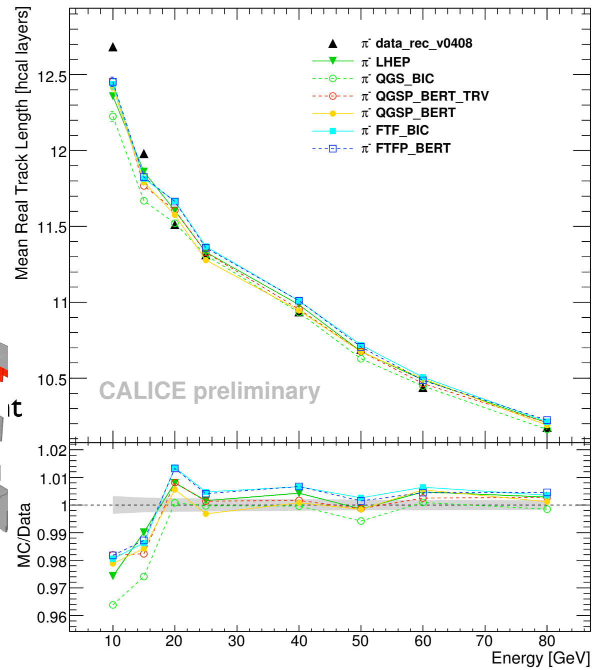
2D profile from starting point

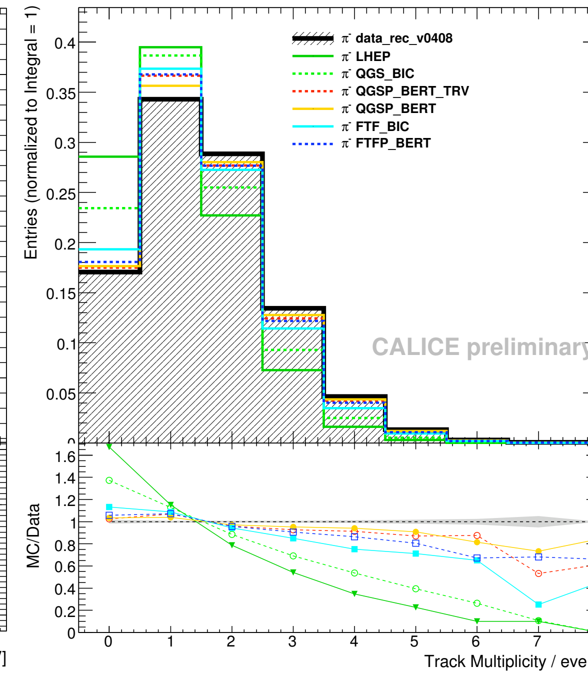
- Present-day simulation quality requires good detector understanding to discriminate
- Fluctuations also well reproduced



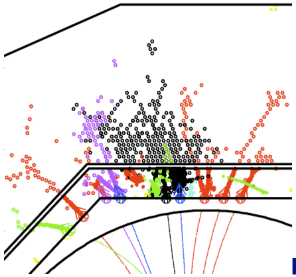
Shower fine structure







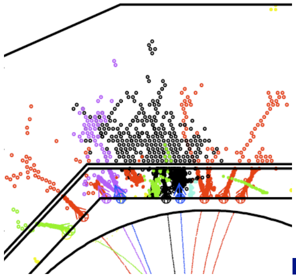
- Could have the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already



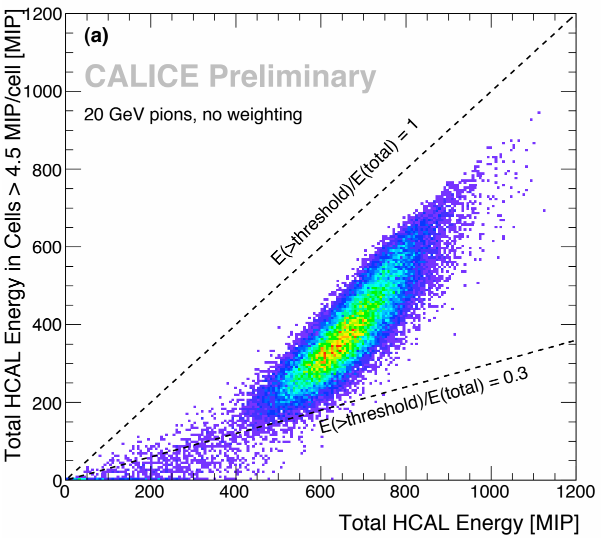
Summary on validation:

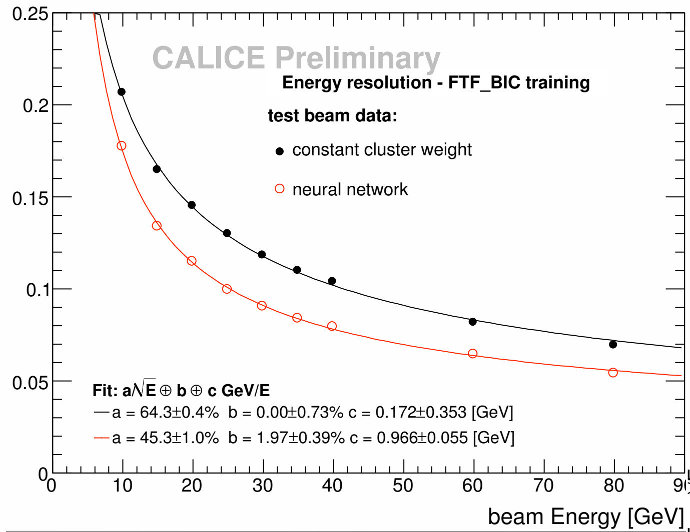
- The particle flow detectors perform as expected
  - support predictions for full-scale detector
- Geant 4 simulations not perfect, but also not as far off as feared a few years ago
  - fruitful close cooperation with model builders ongoing
- Predicted shower sub-structure is seen
  - detailed checks possible, benefits for all calorimeters

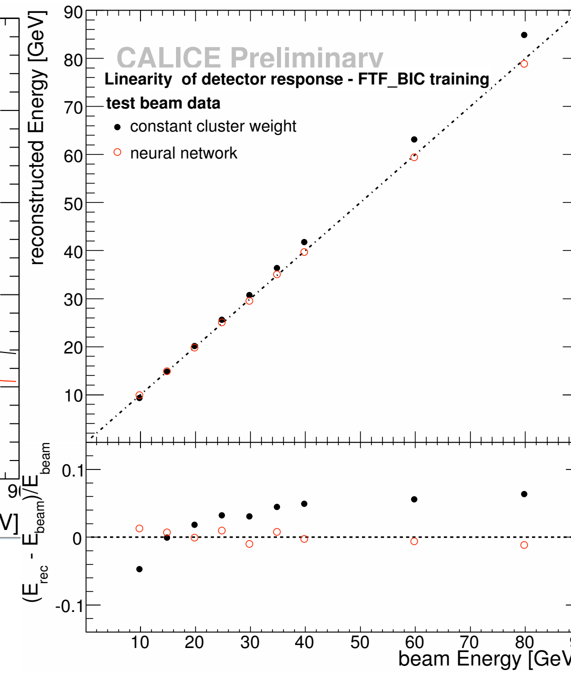
Test the algorithms with real data



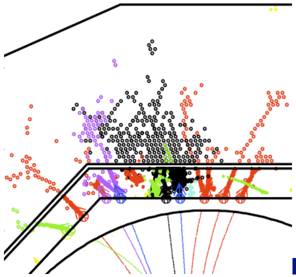
Software compensation



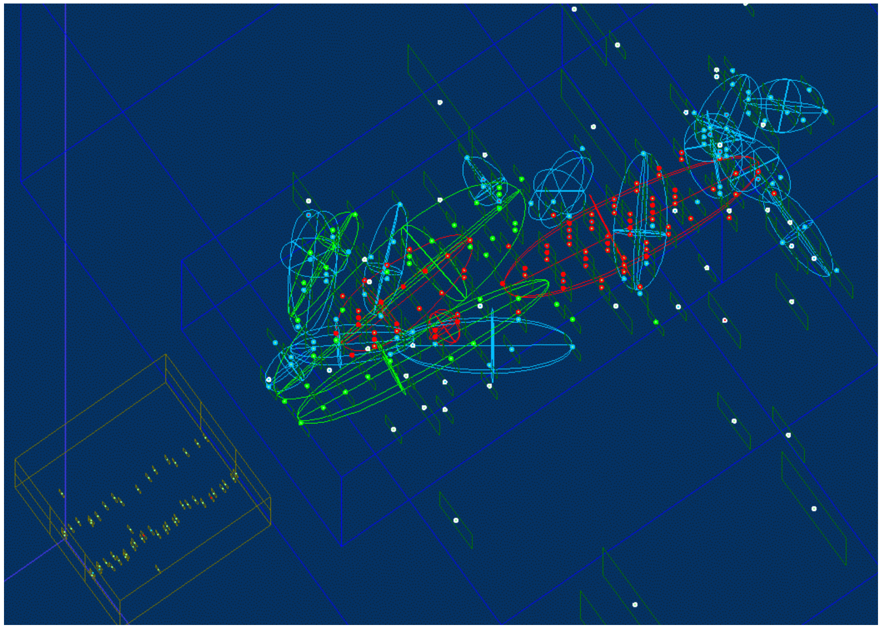


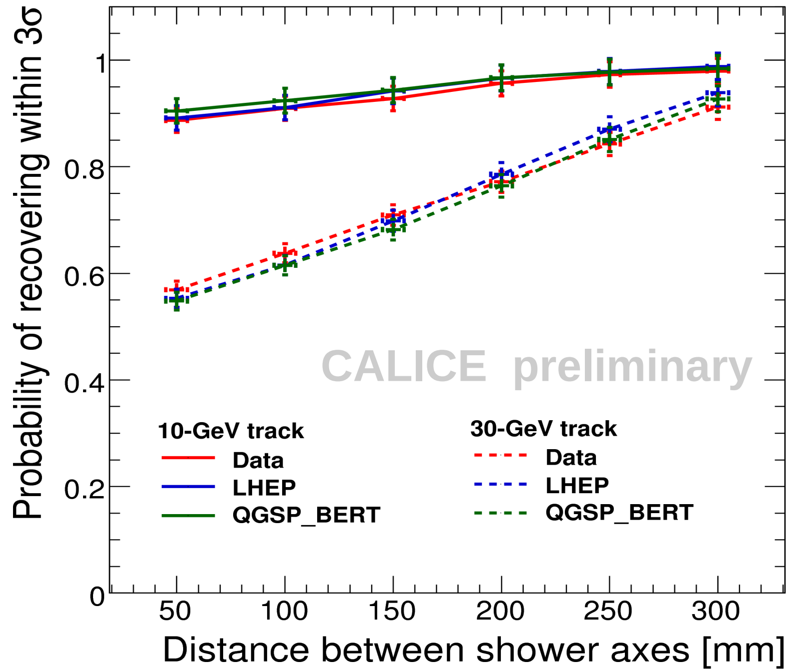


- Poor man's dream
- Significantly improved resolution AND linearity
- High granularity - many possibilities



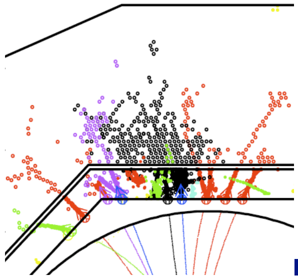
Two-particle separation



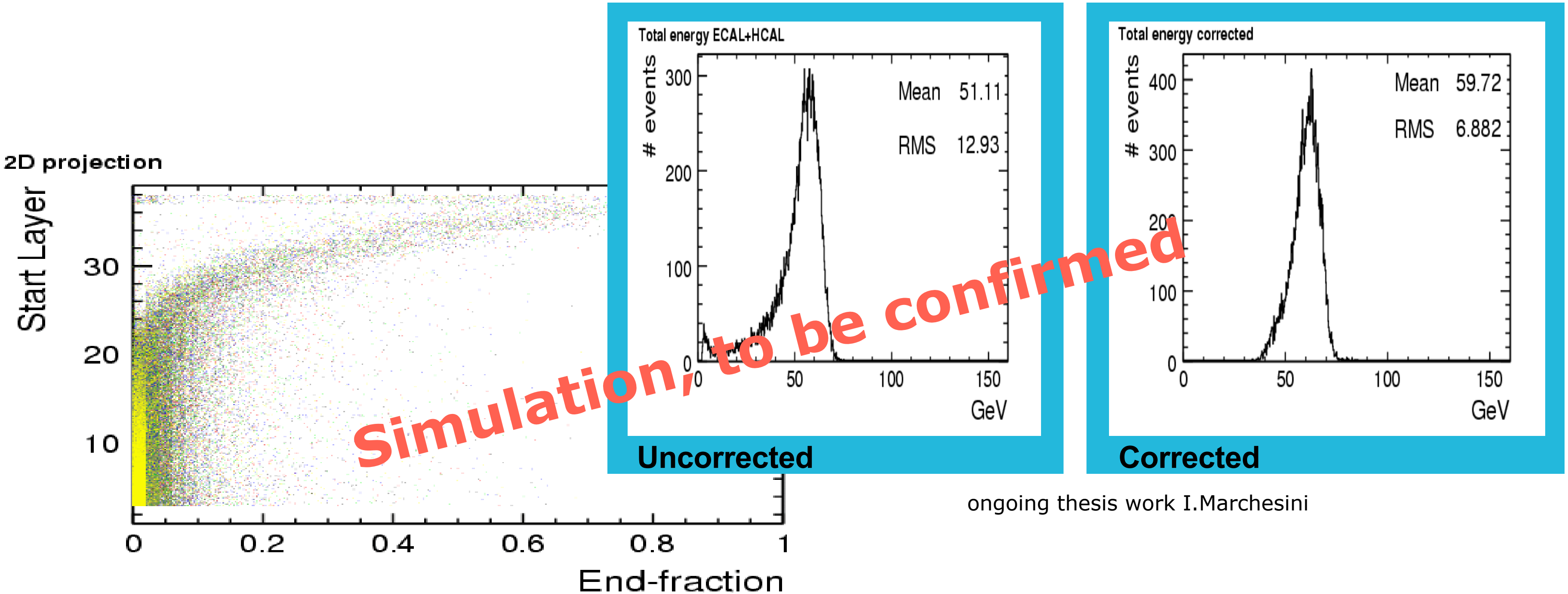


- The “double-track resolution” of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- Important: agreement data - simulation
  - sharing the same limitations

to be done with photons, too

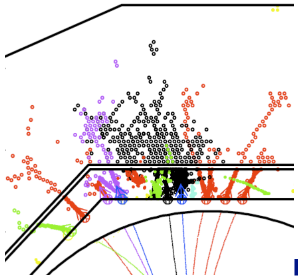


Leakage estimation



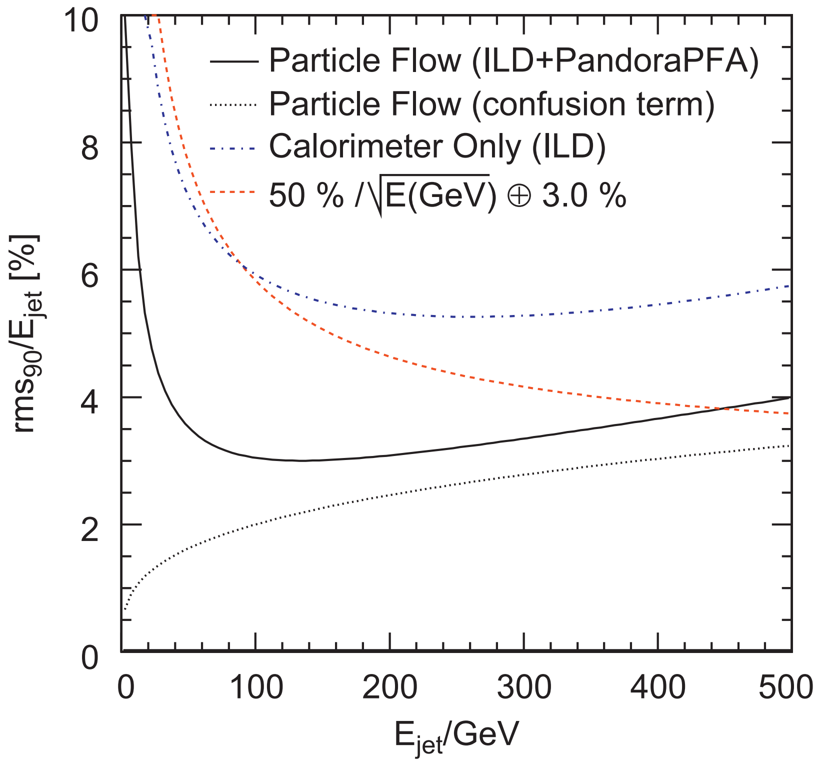
ongoing thesis work I.Marchesini

- Infer leakage from seen part of shower topology and energy
- multivariate techniqes; striking potential
- implications for detector optimization: implement in Pandora

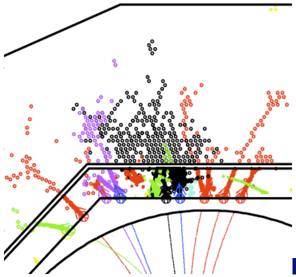


Summary on algorithms

- Granularity is extremely powerful
- Energy resolution and imaging capabilities verified with data at sub-structure level
  - the main drivers of PFLOW performance
- Leakage estimation and software compensation not yet implemented in present Pandora

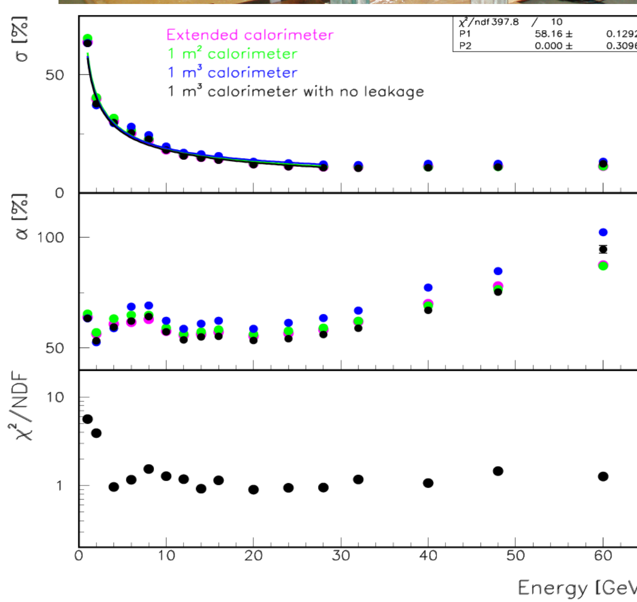


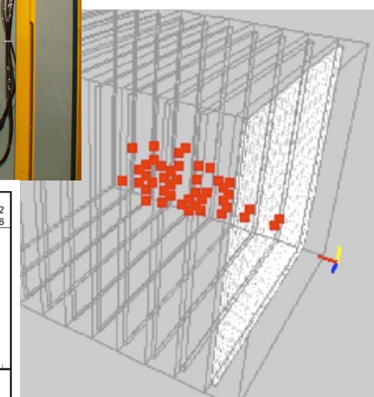
Test the technologies
and establish feasibility

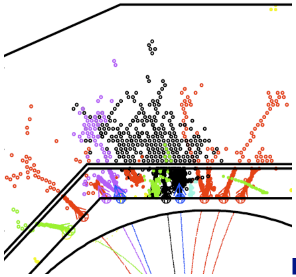


Digital calorimetry

- Digital and semi-digital hadron calorimeter
  - even higher granularity
  - suppress dE/dx fluct.
  - reduced n sensitivity
  - limited at high E?
- Small RPC proto successful
- Educated simulations
- Full-size RPC based prototypes underway

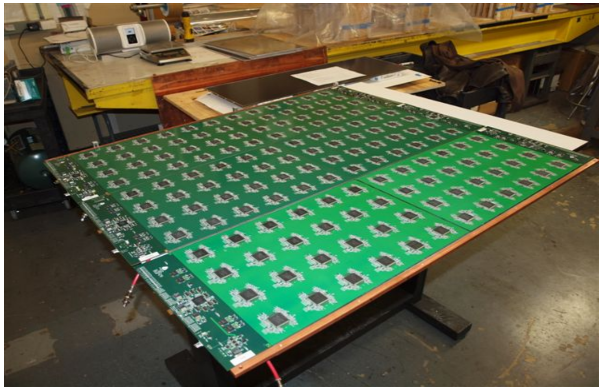




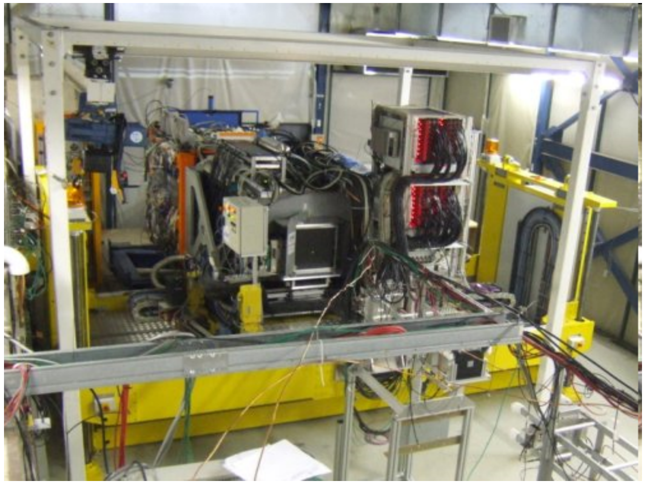


RPC DHCAL m3 at FNAL

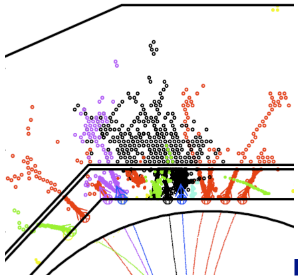
- start in October
- Issues to discuss:



- common running with SiW ECAL
  - possible early in 2011
  - would put DHCAL on equal footing

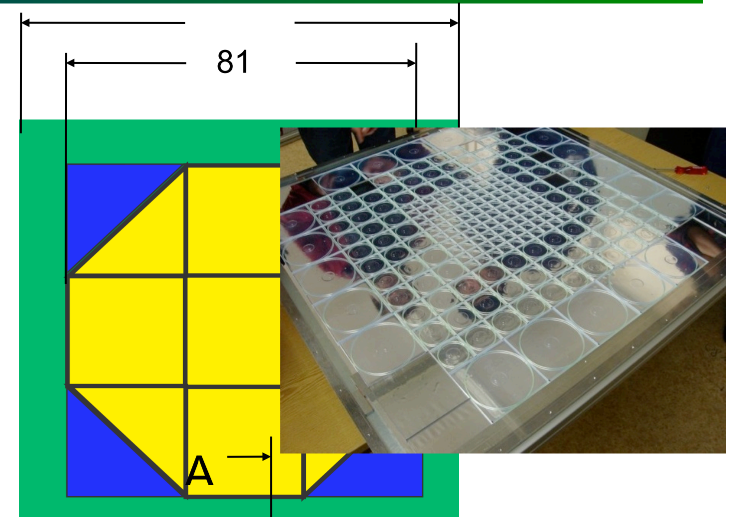


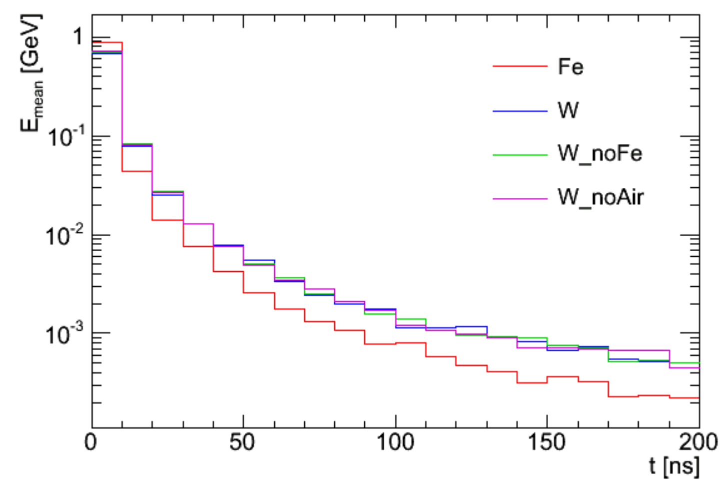
- TCMT intrumentation options
  - presently scintillator strips
  - can be exchanged against RPC
- End date, possible continuation at CERN
  - higher E, higher duty cycle

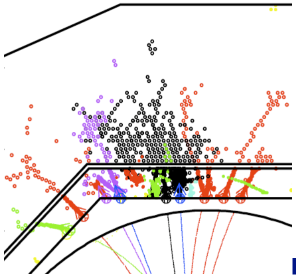


High energy

- Particle flow also a promising option for CLIC energies
- Leakage expected to limit PFLOW performance
  - need 1 λ ECAL + 7 λ HCAL
- Tungsten absorber cost-competitive with larger coil - and less risky
- Test beam validation with scintillator and gas detectors
- More neutrons:
  - different model systematics
  - timing measurements

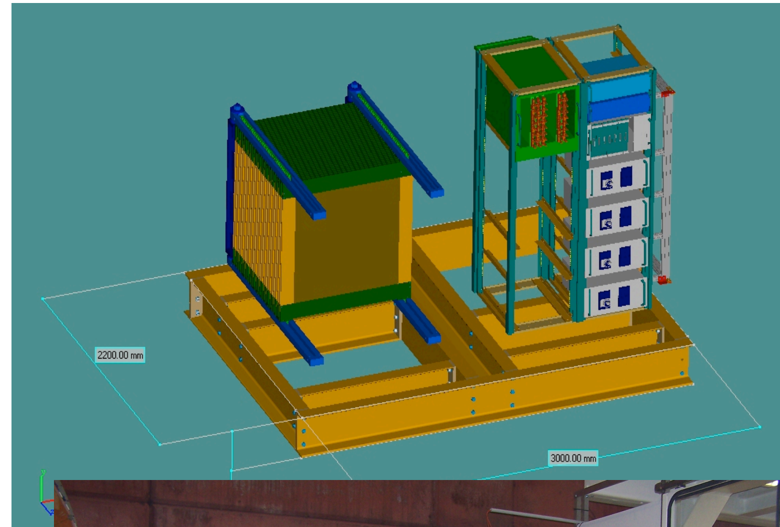


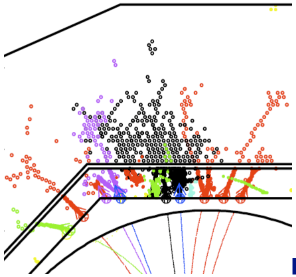




Tungsten beam test plans

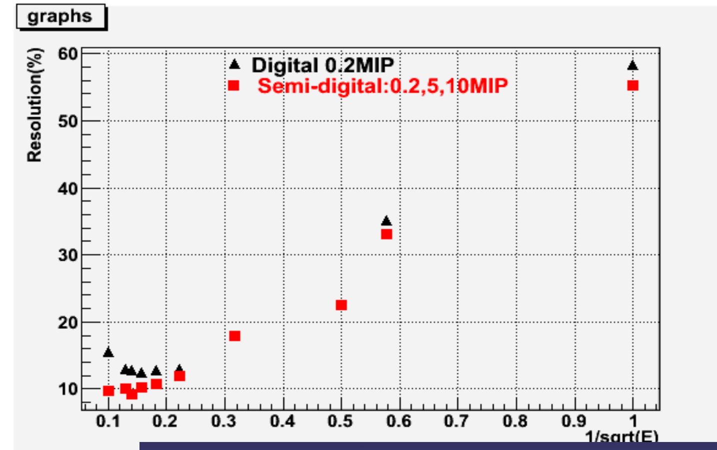
- start at CERN PS: Sep 2010 muons, Nov 2010 hadrons
- 30 layers initially, more 2011
- scintillator layers modified (finer pitch), re-commissioned
- begin with static set-up, integrate into movable stage later
- move to SPS ~ end 2011
- integrate few layers of gaseous detectors parasitically, full test later
- future: test with scintillator and 2nd generation time-resolving electronics
  - neutron timing, time stamping

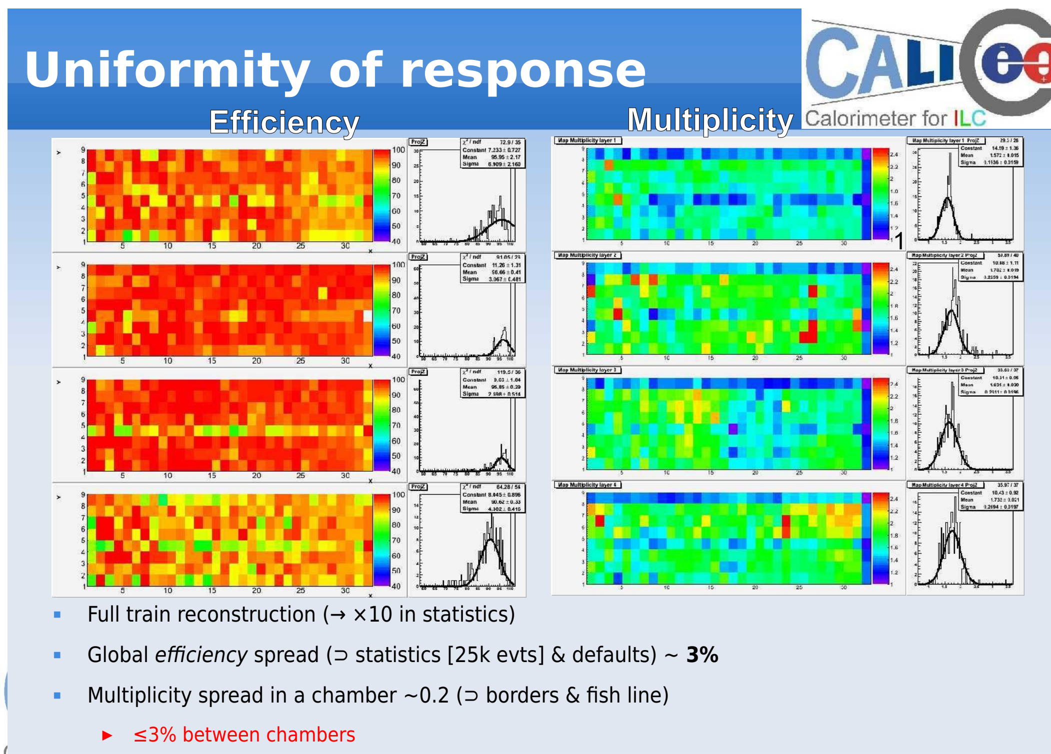


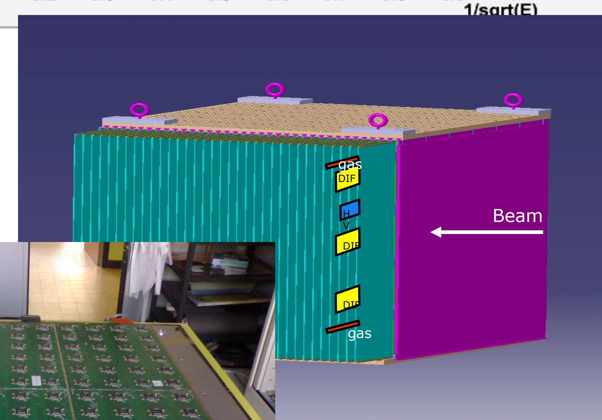


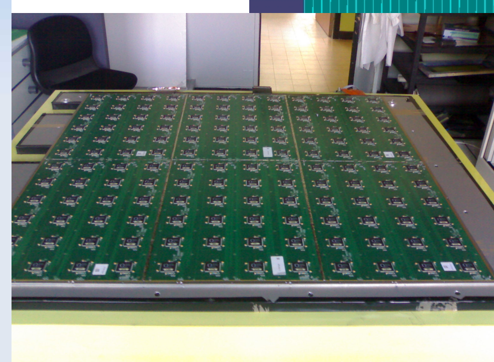
Semi-digital GRPC HCAL

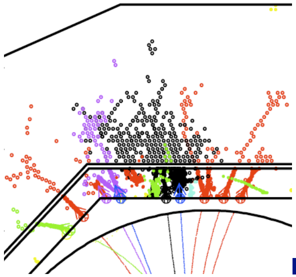
- idea: recover high energy resolution
- aim at cubic-metre ~ 2011
- will need stage at some point
- 3 layers built





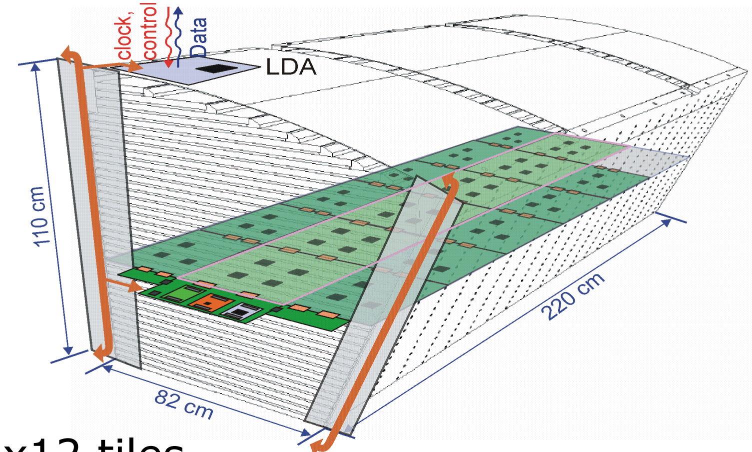




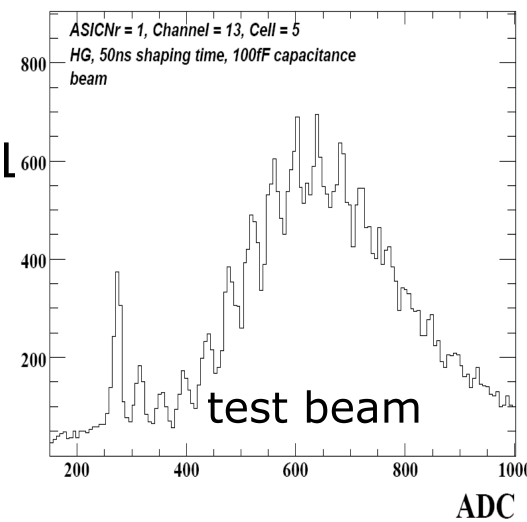


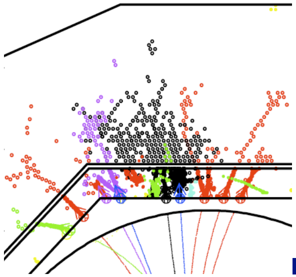
Scint HCAL: 2nd generation

- integrate readout ASICs and LED system
  - include ADCs and TDCs
  - power pulsing, zero suppression
- Different options for photo-sensor
- Different options for coupling
  - via WLS fibre or direct
  - pins or SMD SiPMs (NIU)
- Interfaces to be done
  - cooperaton with NIU/FNAL
- Performance: minical
  - ~12 layers, em showers
- Later: tungsten HCAL
  - and steel wedge



12x12 tiles, 36x36 cm2





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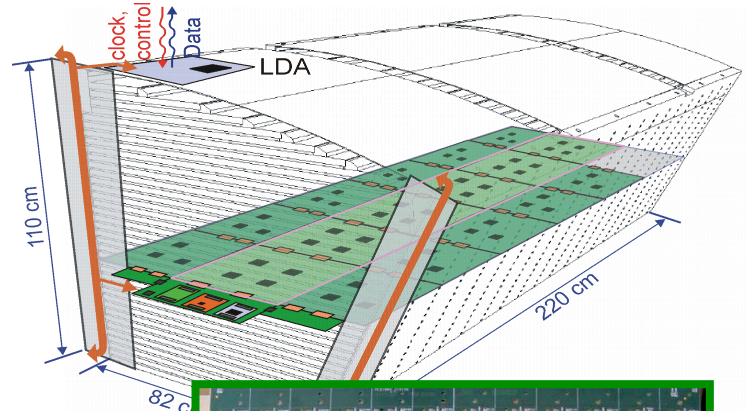

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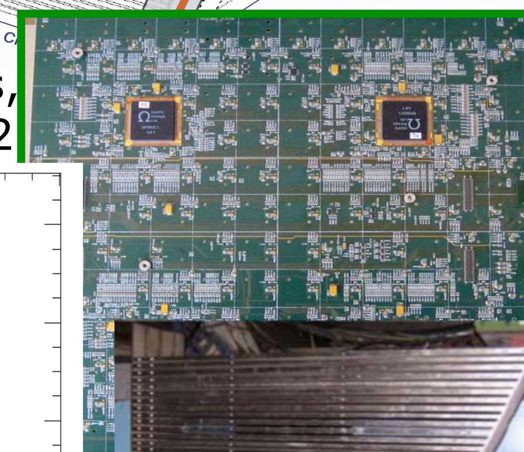
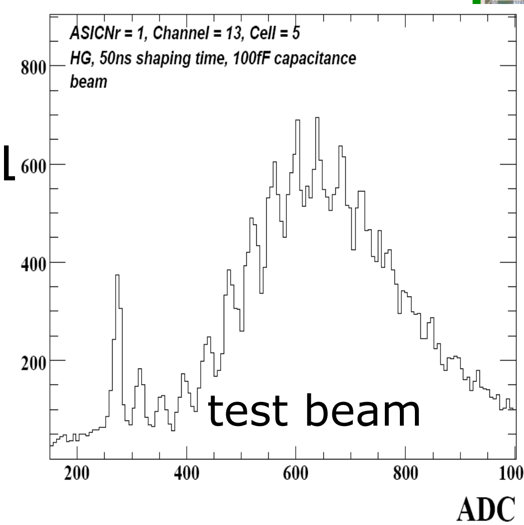
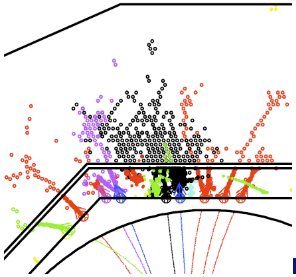




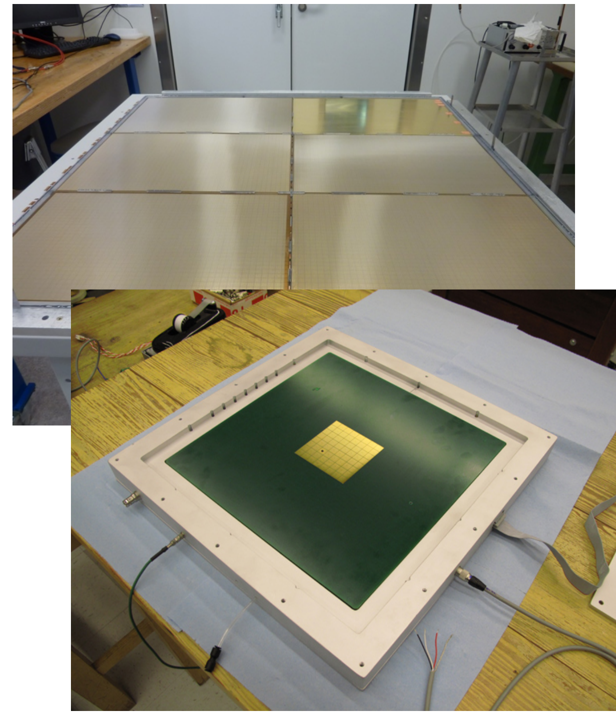


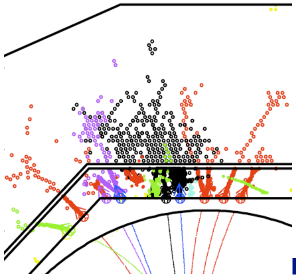
(S)DHCAL options

- Micromegas
  - 1m2 built
  - new ASIC MicroROC
  - see Jan Blaha's talk
  - parasitic test with W in 2010

- GEMs
  - moving to larger area modukes with KPix chips
  - beam tests 2010-11

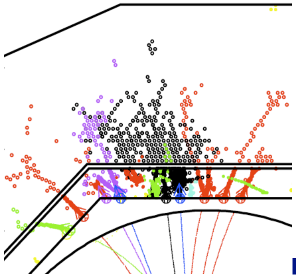
- Most likely no full scale hadron tests, but addressing the critical integration issues





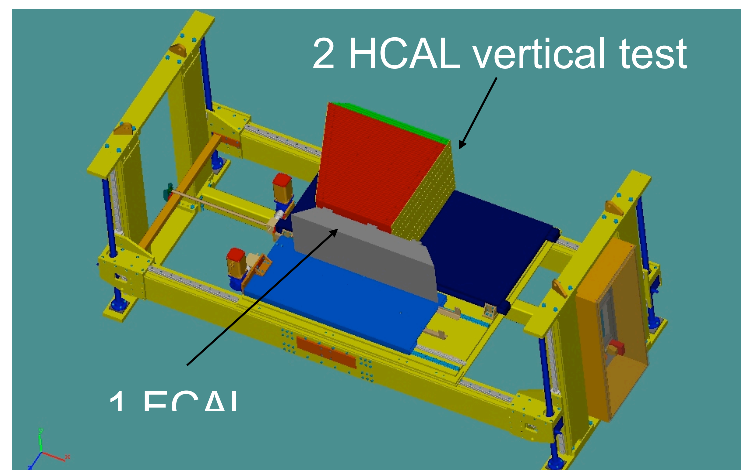
Summary on technologies

- a leap in several orders of magnitude in channel count
- new sensor technologies, new integration concepts
  - the latter is part of the feasibility demonstration
- progress towards realism:
  - realistic designs
  - realistic simulations
  - realistic cost
  - realistic proposal
- Digital calorimetry ready for exploration

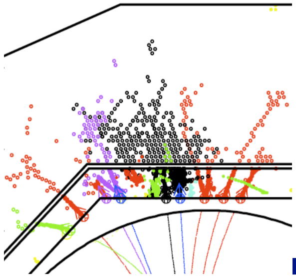


Conclusion

- Particle flow calorimetry does not solve the inherent problems of hadron calorimeters
- But it holds the promise of providing a highly performant work-around
- Focussed program: thrust is in
  - completing the large scale physics tests for all active and passive media
  - demonstration of integration feasibility
- Increased test beam activity 2011-12
- Aim at central installation



Back-up slides

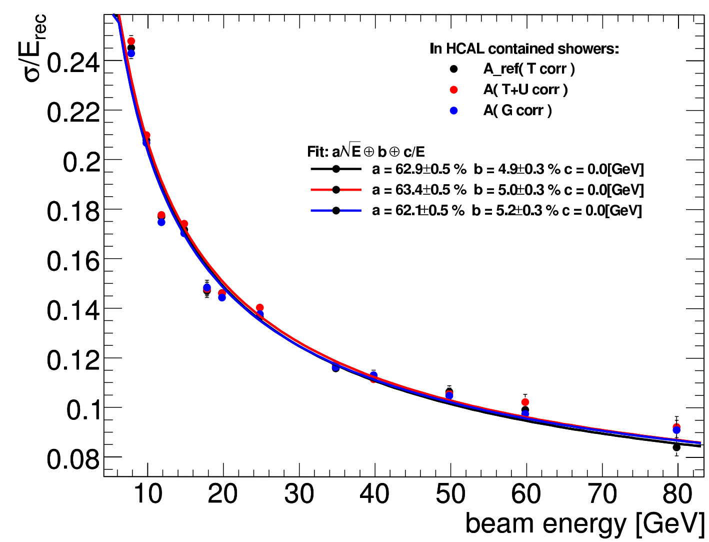


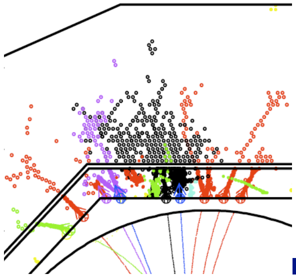
Calibration

- Study triggered by review of LC detector LOI
- Can you calibrate millions of channels and maintain stability?
  - not really a worry for Si, but could be an issue for scintillator

- 1. Simulate impact of statistic (uncorrelated) and systematic (correlated) calibration errors, find $\int L$ for in-situ calibration
  - PFLOW performance VERY robust w.r.t. channel-to-channel variations; coherent effects easy to control

- 2. Exercise in-situ methods (SiPM auto-calib, track segments) with test beam data from CERN and FNAL
  - transport calibration across the ocean and restore performance





Integration

- Sensor technology, precision mechanics
- Next: system engineering

- Industrialized ASIC development using common building blocks

- New operational challenges
  - power pulsing
  - on-detector zero suppression
  - real-time threshold monitoring
  - time measurement

SDHCAL Scint E/HCAL

spin-off Si ECAL